



Snow formation and precipitation



Lots of snow in some places...

Most in 12-month period: 31.5 m
1971/72, Mt. Rainier, WA, US

Most in 1 winter: 29.0 m
1998/99, Mt. Baker, WA, US

Most in one calendar month: 9.91 m
January 1911, Tamarack, CA, US

- Most in a 24-hours period: 1.98 m
1963, Thompson Pass, AK, US

(Snow depth, not SWE)



Evidently, all this snow forms in the atmosphere prior to precipitation.

Humidity and saturation

Cooling of air

Lifting mechanisms

Crystal formation

Classification of
atmospheric snow



Composition of dry atmosphere

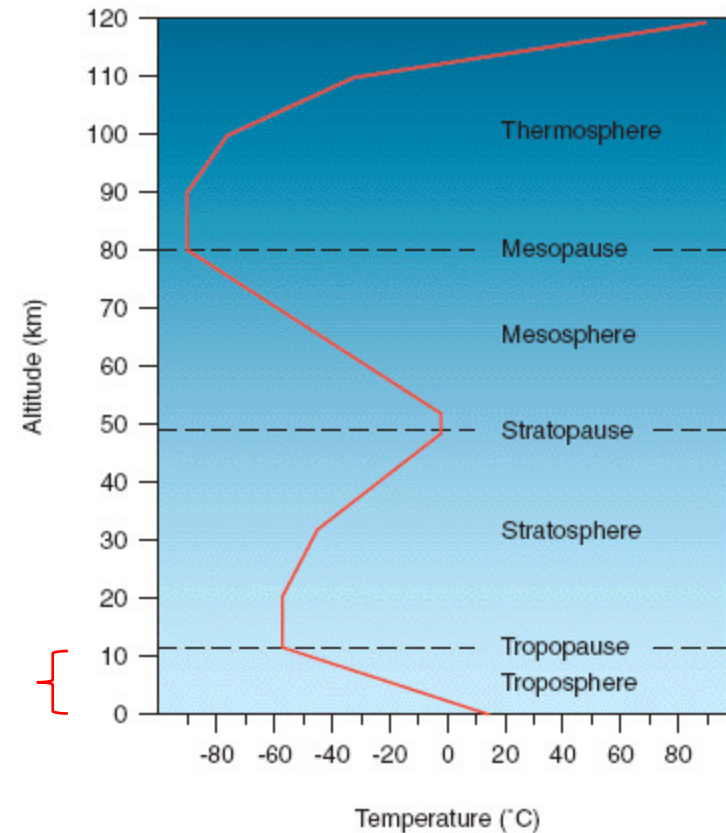


Ideal gas law: $pV = nRT$

R = univ. gas const.: 8.314 [J/mol/K]

Valid assumption: air as a mixture of ideal gases

Gas	Concentration [%]	[ppmv]
N ₂	78.084	780'840
O ₂	20.946	209'460
Ar	0.934	9'340
CO ₂	0.042	425
Ne, He, CH ₄ , Kr, H ₂ , N ₂ O, CO, Xe, O ₃		



Atmosphere: dry air (incl. trace gases) + water vapor [+ particles (aerosols)]



Dry air			
Molecular weight	28.966	g/mol	M
Spec. gas const.	287.04	J/(kg K)	R _d
Spec. heat cap., f(T)	1005	J/(kg K)	c _{p,d}
Density @ STP*	1.2923	kg/m ³	ρ
Water vapor			
Molecular weight	18.016	g/mol	M
Spec. gas const.	461.5	J/(kg K)	R _w
Spec. heat cap., f(T)	1846	J/(kg K)	c _{p,w}

* STP: 0°C, 1000hPa

$$pV = nRT; \quad R' = R/M \rightarrow R = R'M$$

$$pV = nMR'T; \quad \text{with } nM = m$$

$$pV = mR'T$$

$$p = \frac{m}{V} R'T = \rho R'T \rightarrow \rho = \frac{p}{R'T}$$

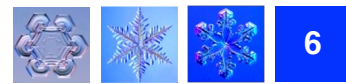
M: molar mass [g mol⁻¹]

n: number of mols

R': specific gas constant [J kg⁻¹ K⁻¹]

m: mass [kg]

ρ: density [kg m⁻³]



total atmospheric pressure is the sum of the partial pressures of all atmospheric constituents (Dalton's law)

$$p_{\text{tot}} = \sum_i p_i$$

vapor pressure (e) is the partial pressure exerted by water vapor

consequently, pressure of **dry air** $p_{\text{dry}} = p_{\text{tot}} - e$, where $e = e_s \text{ RH}/100$

saturation vapor pressure (e_s) is the maximum vapor pressure that is thermodynamically achievable for a given temperature, **however:**
super-saturation exists under certain conditions

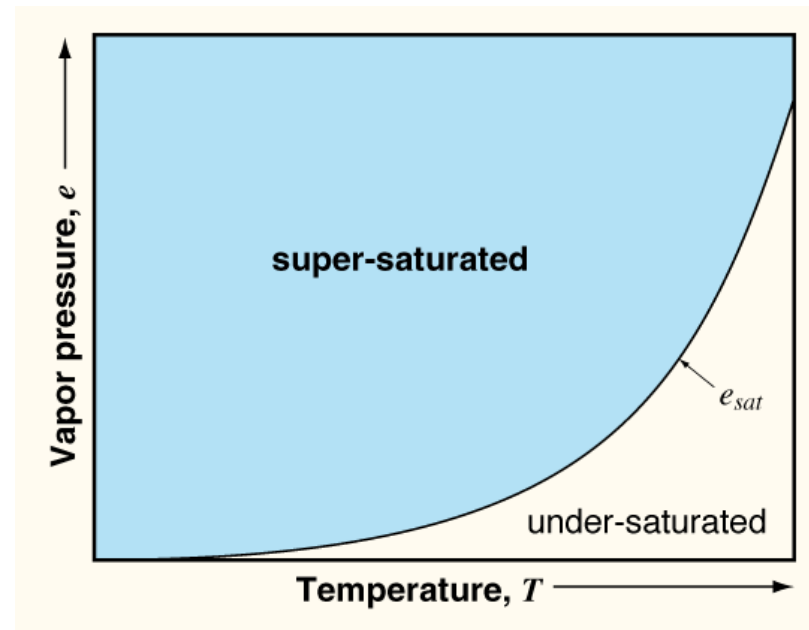
→ Def. super-saturation:

vapor pressure of a compound that has a higher partial pressure than the saturated vapor pressure of this compound.

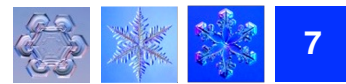
X% super-saturated.

→ Def. water vapor:

H₂O molecules (invisible),
not droplets (fog, clouds, etc.)



Saturation vapor pressure

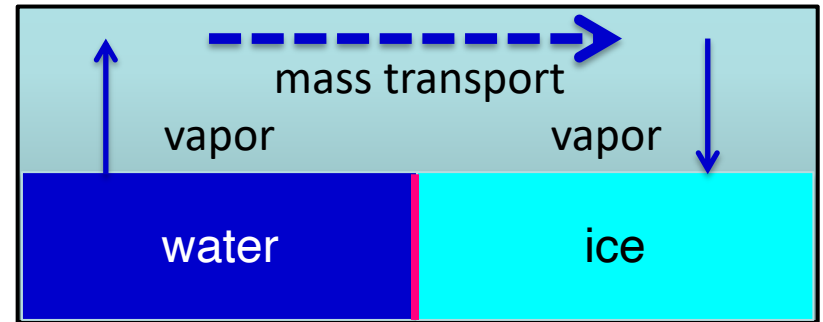
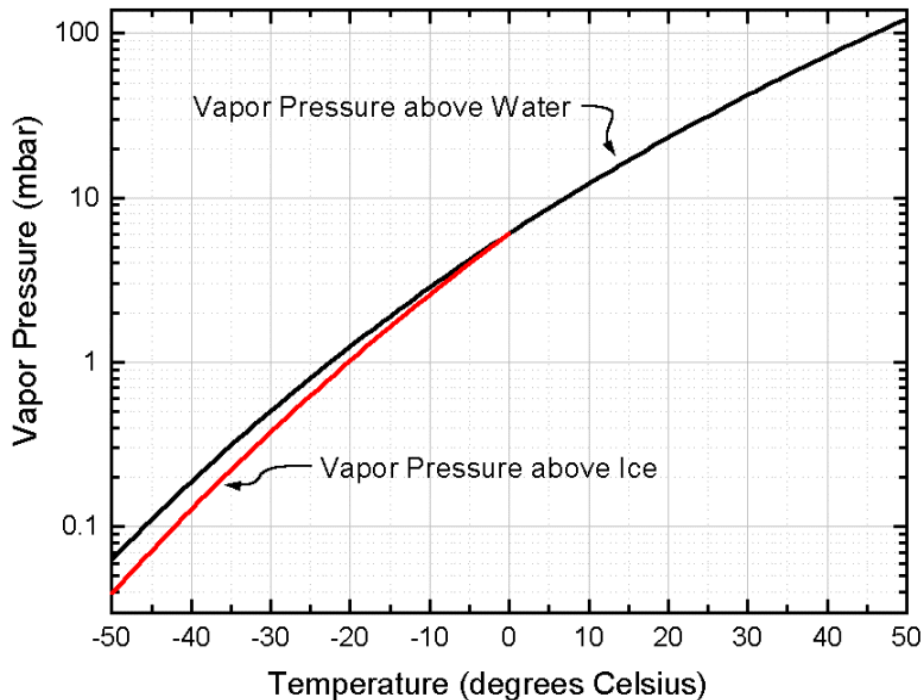


strong $f(T)$, recall: Clausius-Clapeyron equation
different over water ($T > 0^\circ\text{C}$) and ice ($T < 0^\circ\text{C}$) surfaces
various approximations (equations) available (both for water and ice)

$$\Delta e_s = e_{s,w} - e_{s,i} \approx \text{avg } 0.2 \text{ mbar}; \text{ max: } 0.27 \text{ mbar}$$

$$e_{s,w} > e_{s,i} \text{ for all } T$$

Log-scale!



closed box, constant $T \leq 0^\circ\text{C}$

$$e_{s,w} > e_{s,i}$$

See also slides in “Snow Properties”

The water molecule



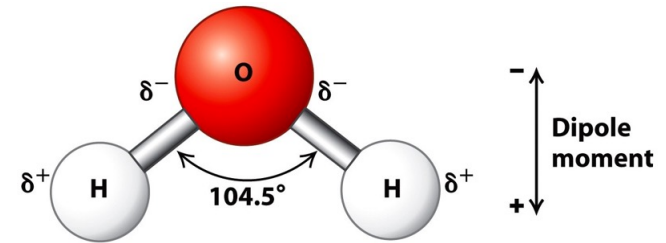
H₂O is a dipolar molecule, good solvent and adhesive
Oxygen: 8 protons, 8 neutrons, 8 electrons (16 g mol⁻¹)
Hydrogen: 1 proton + 1 electron (1 g mol⁻¹)

Covalent bonds between O and H

Hydrogen bonds develop from ion pairs of electrons

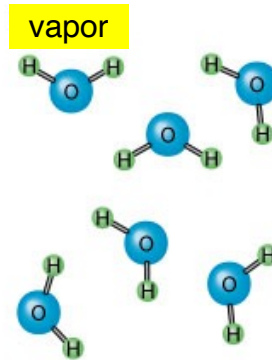
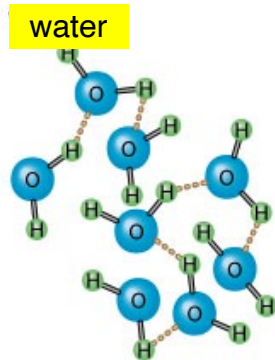
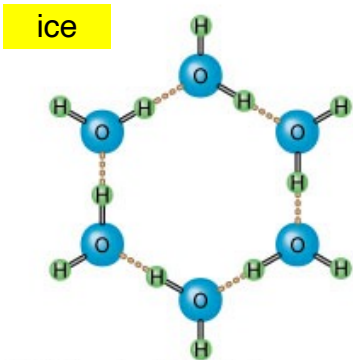
Hydrogen bonds cause cohesion among molecules:

ice > liquid > vapor



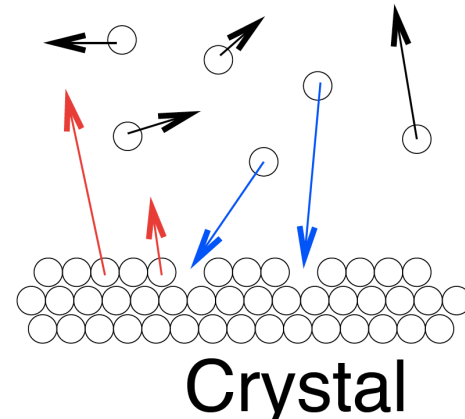
Angle: 104.5° for liquid
109.0° for ice

The physical states of water



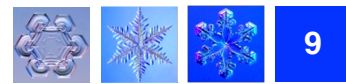
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Vapor



Crystal

What is an Ice Crystal?

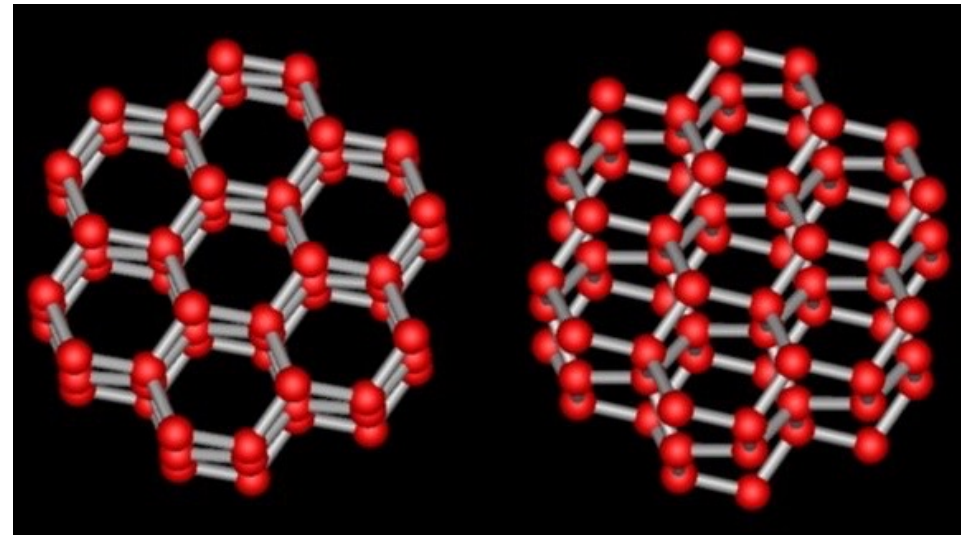
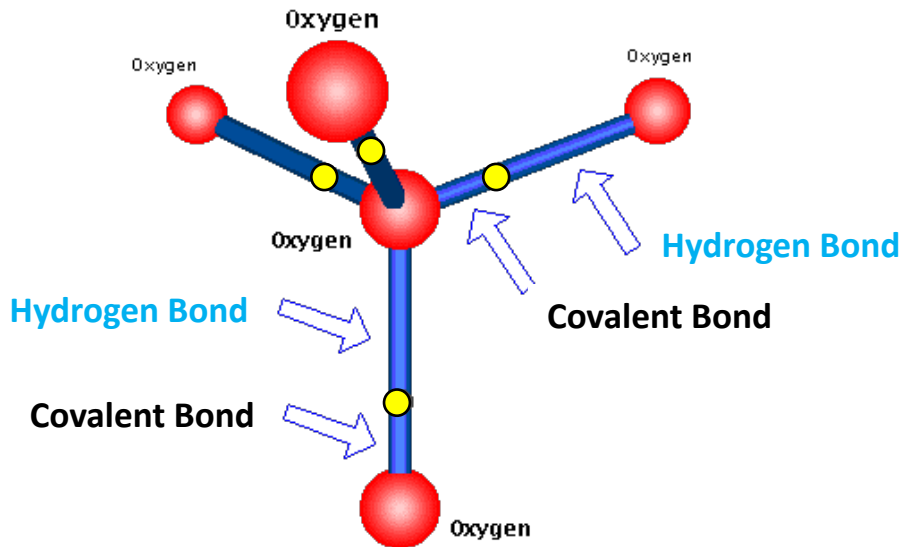


Each O has 4 nearest neighbors with which it shares an H (104.5°)

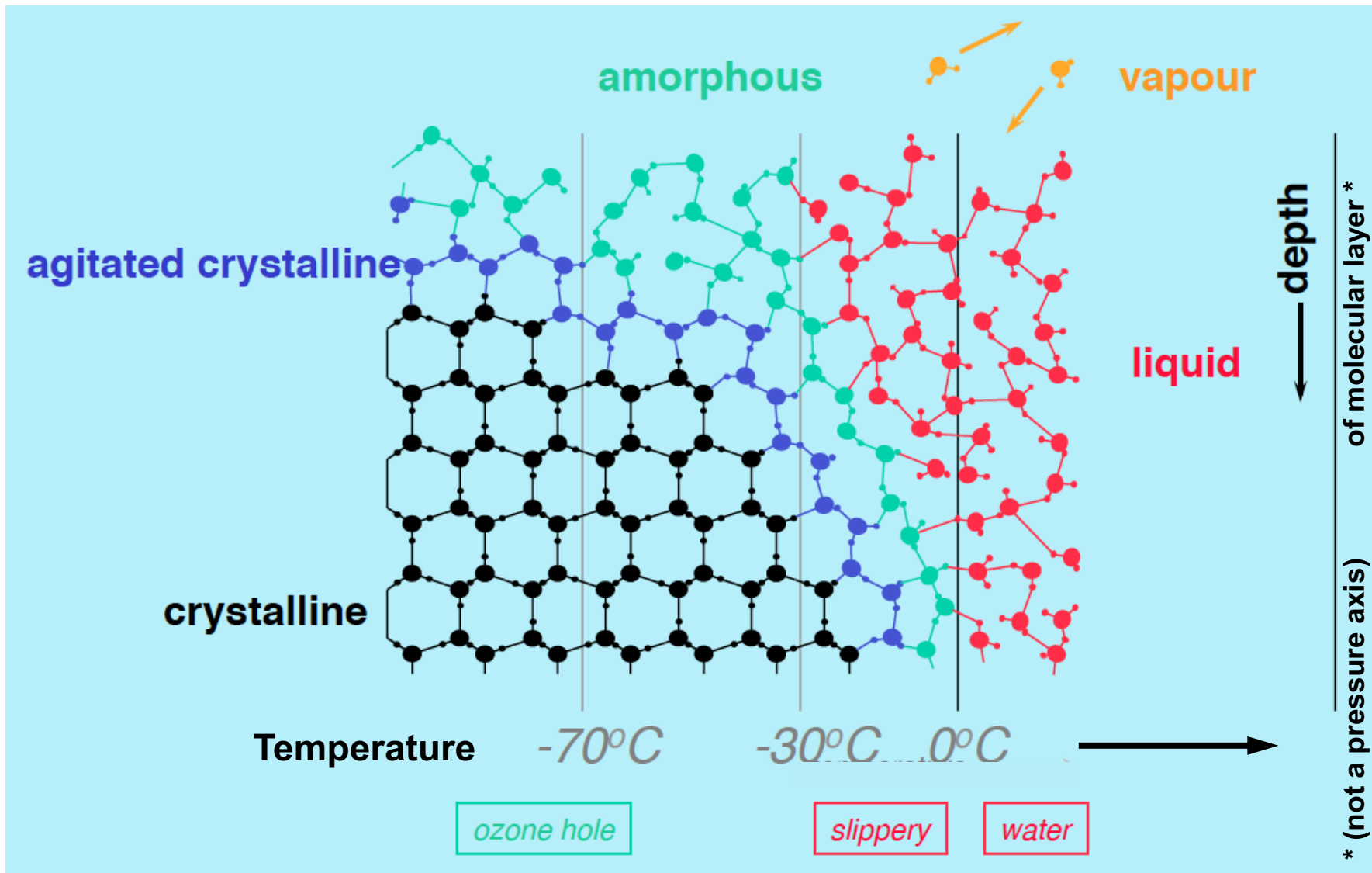
H_2O molecules are aligned/coordinated in a **hexagonal** lattice structure, reason why snow crystals (and snowflakes) have a hexagonal geometry

Geometrically, this is a more open structure than water \rightarrow **lower** density

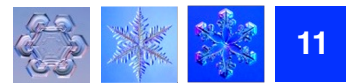
water: 1000 kg/m^3 , ice: 917 kg/m^3



hydrogen bonds are weaker than **covalent bonds**, i.e., break up easier



Mechanisms of vapor (mass) transport



$e = f(T)$

$e = f(\text{geometry of droplets and crystals})$

e over convex surf. (tips, points, corners, edges, ridges)

e over concave surf. (necks, depressions, grooves, etc.)

> than over flat (weaker molecular bonds)

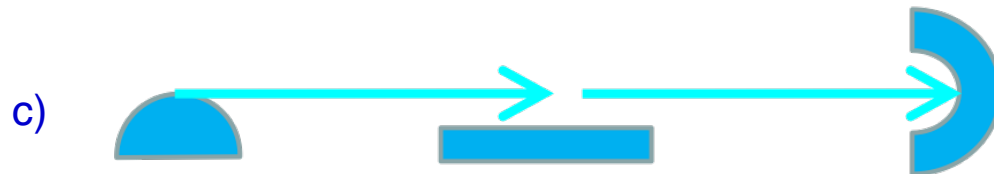
< than over flat (stronger molecular bonds)



$e_w > e_i$



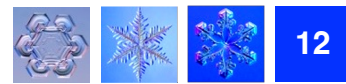
temperature



curvature: $e_{\text{convex}} > e_{\text{flat}} > e_{\text{concave}}$



size (curvature)



mixing ratio: mass of vapor per *unit mass* of **dry** air;

$$m = \rho_v / \rho_d \text{ [kg/kg]}$$

specific humidity: mass of vapor per *unit mass* of **moist** air;

$$q = \rho_v / \rho \text{ [kg/kg]}, \text{ with } \rho = \rho_v + \rho_d$$

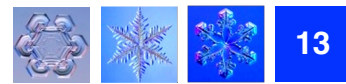
absolute humidity: mass of water per *unit volume* of **moist** air;

$$a = m_w / V_a \text{ [kg/m}^3\text{]}$$

relative humidity: ratio of the *actual* vapor pressure to the *saturated* vapor pressure in percent;

$$RH = e / e_s * 100 \text{ [%]}$$

dew point: temperature at which **saturation/condensation** occurs if air is cooled at constant pressure without a change in the quantity of water vapor available



What is needed to form (solid) precipitation? (→ 3 main conditions: ...)

sufficient **moisture** in the air

(moisture source, and atm. circulation to transport moisture;

this finally explains in part the spatial snow distribution and climatology)

presence of condensation **nuclei** (aerosols: dust, soot, salt, ice, pollen, etc.).

cooling to cause condensation: a) reach saturation, b) condensation

→ Result: formation of clouds, i.e., liquid and/or solid water particles in the air

Which processes cause cooling of the air? (→ 5 mechanisms: ...)

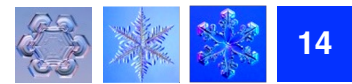
a) **Lifting** (altitude), b) **Advection** (latitude), c) **Radiative cooling** (local)

d) **mixing** with colder air (diabatic), e) **contact** with cold surfaces

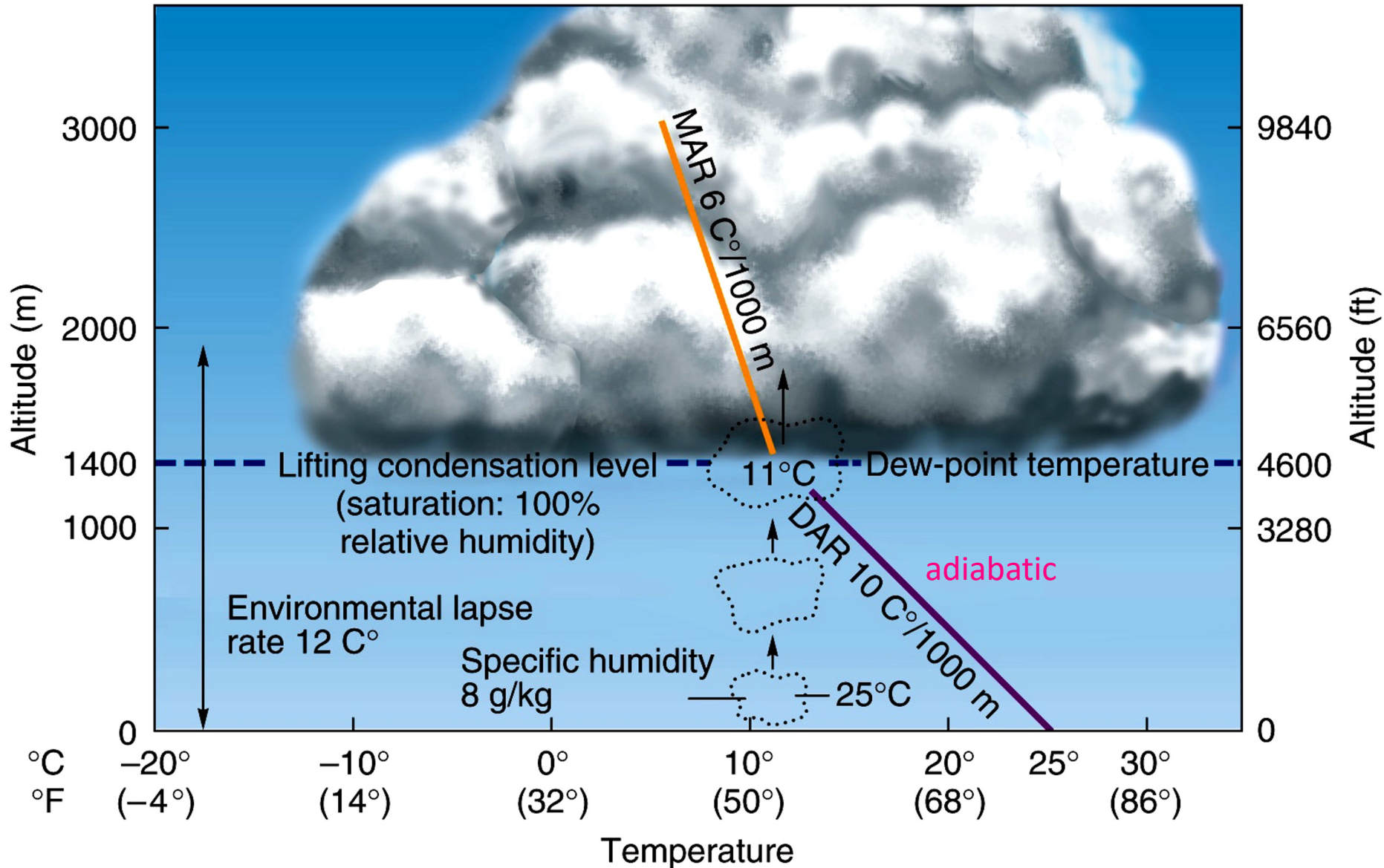
Lifting mechanisms: (→ 4 mechanisms: ...)

1. Orographic lift
2. Frontal lift
3. Convergence
4. Convection

Lapse rates

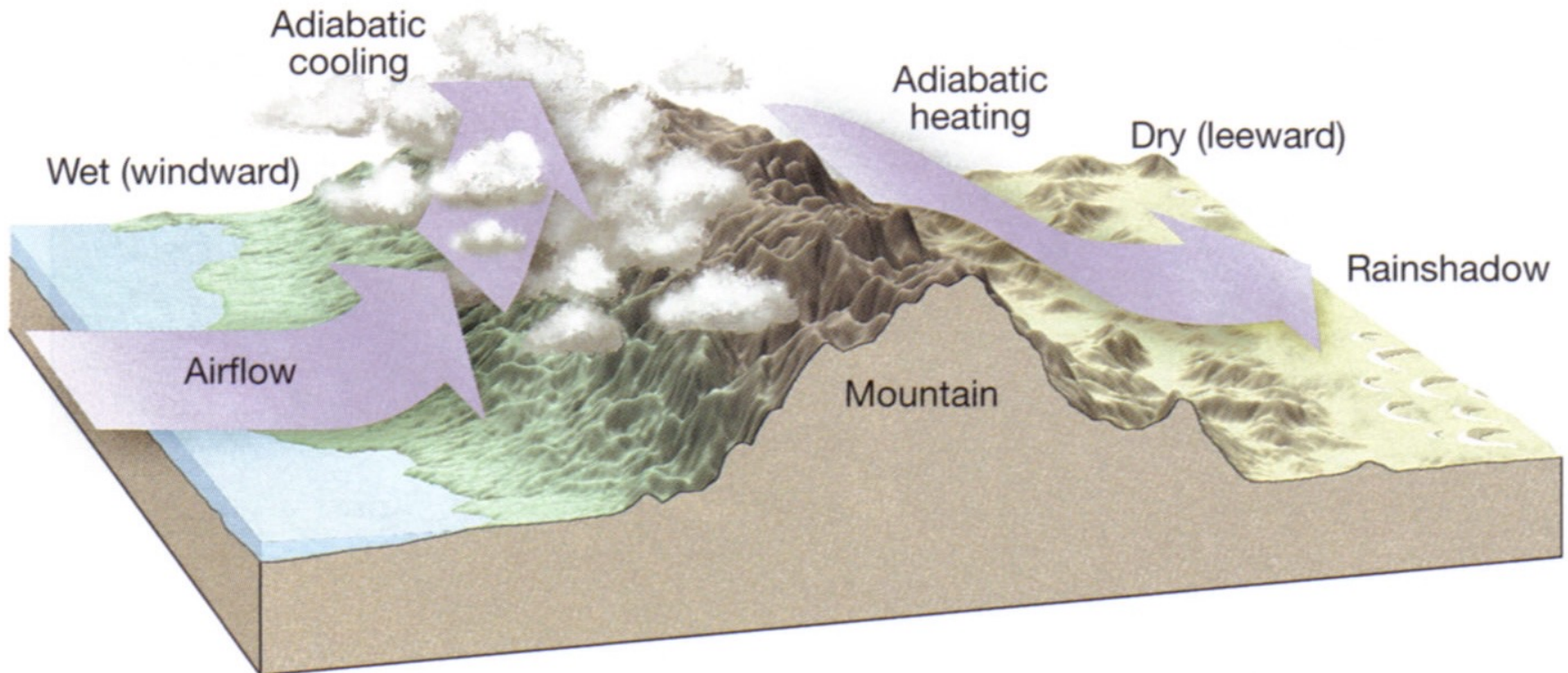


recall course "Physics and Chemistry of the Atmosphere", Ba6, ENV-320

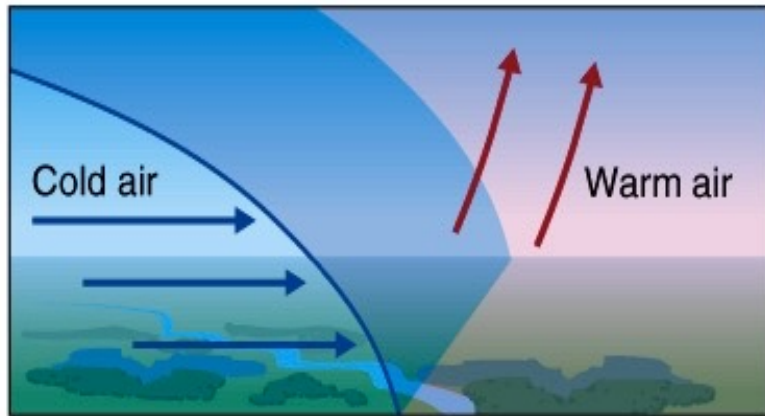


Windward vs. leeward side differences

- Orographic uplift: adiabatic cooling (DAR), condensation occurs when dew point is reached (cloud formation), → precipitation and continued cooling (MAR), with $MAR < DAR$
- Subsidence: adiabatic heating (DAR), drying → **Föhn**

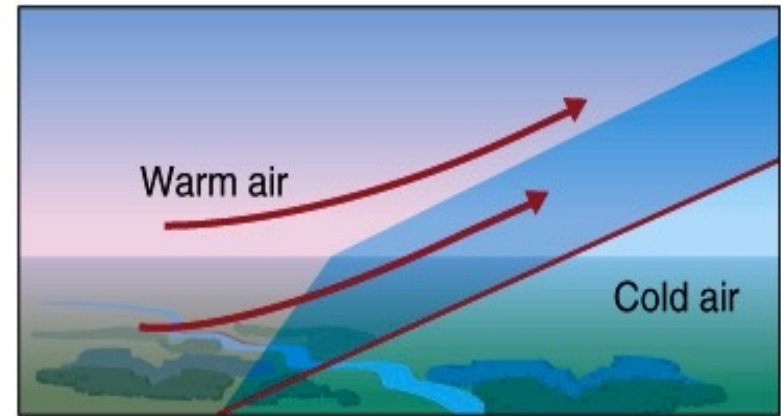


- Along **boundaries** between air masses of unlike temperatures (fronts), the warmer air mass is lifted above & over the colder air mass – why?
- Warm air is cooled by **adiabatic** cooling and, when saturation occurs, clouds will form
- **Cold fronts:** warm air is displaced (lifted) by cooler air
- **Warm fronts:** warm air slides (rises) over cold air



(a) **Cold Front** $v_{\text{cold}} > v_{\text{warm}}$

steep, rapid lifting, intense precipitation,
relatively small extent, shorter duration



(b) **Warm Front** $v_{\text{cold}} < v_{\text{warm}}$

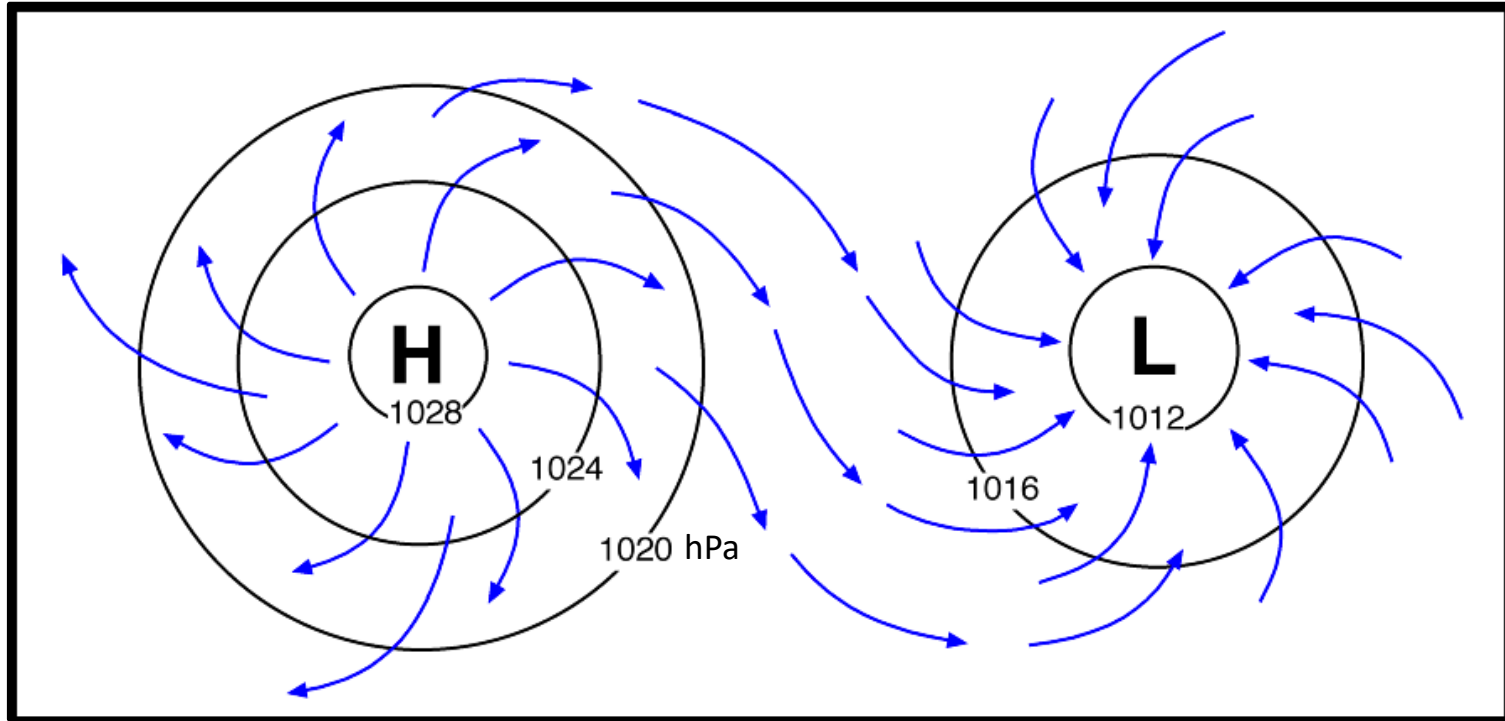
lower precipitation intensity, spread over
broader area, longer lived

Convergence (and Divergence)



Divergence

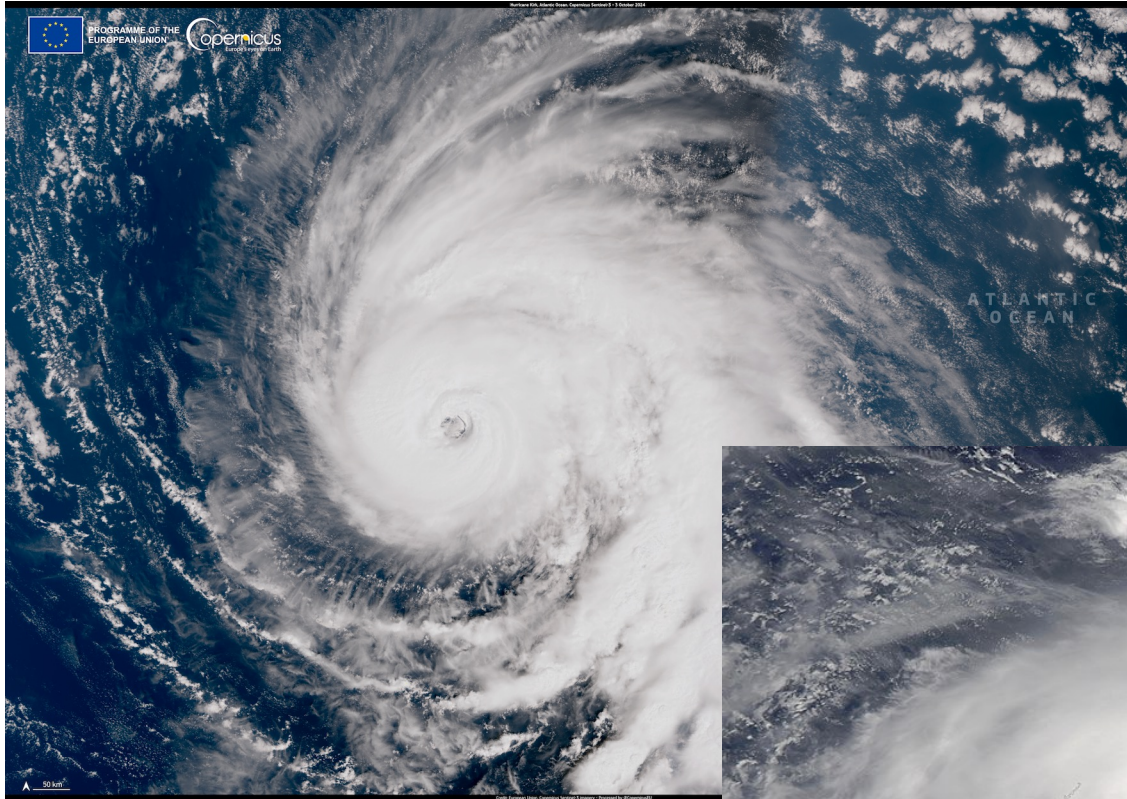
Convergence



Convergence around a low-pressure area (diameter of about 1,000 km) causes **uplift**, cooling, and widespread precipitation.

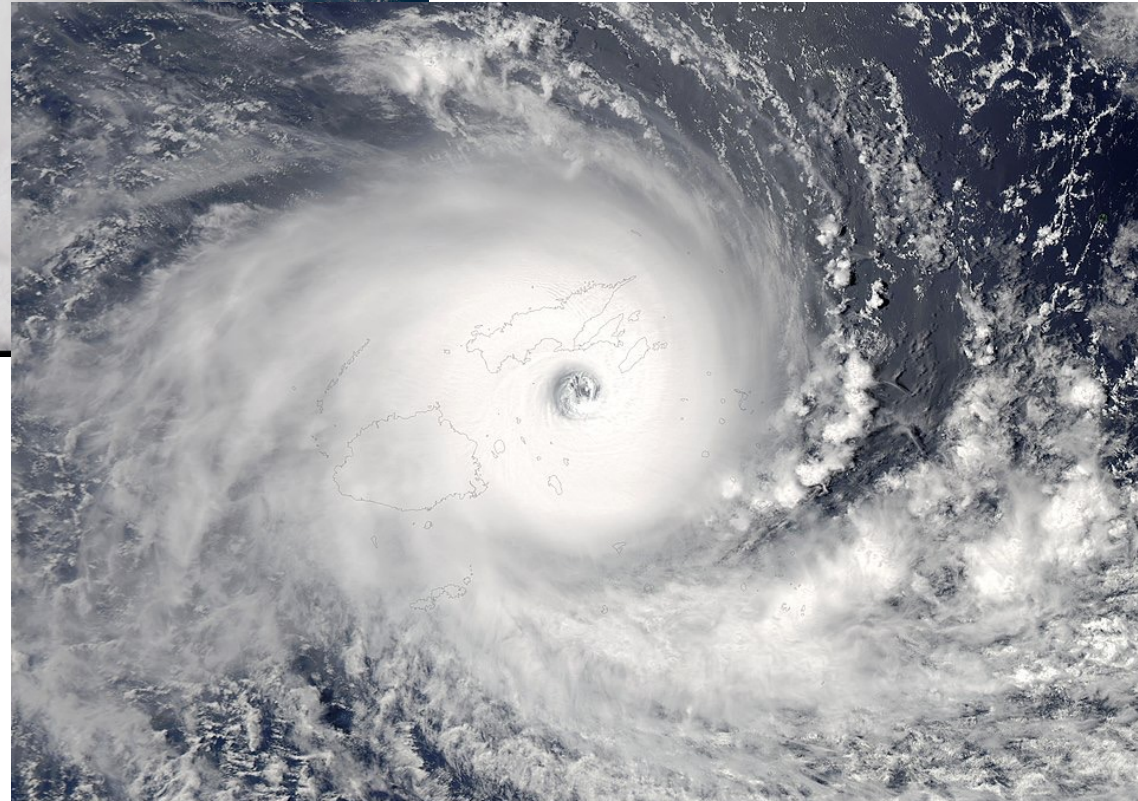
Divergence around a high-pressure area causes **sinking** (subsidence) & clearing skies.

(Above: Northern hemisphere example. How about S – hemisphere? Different? Why?)



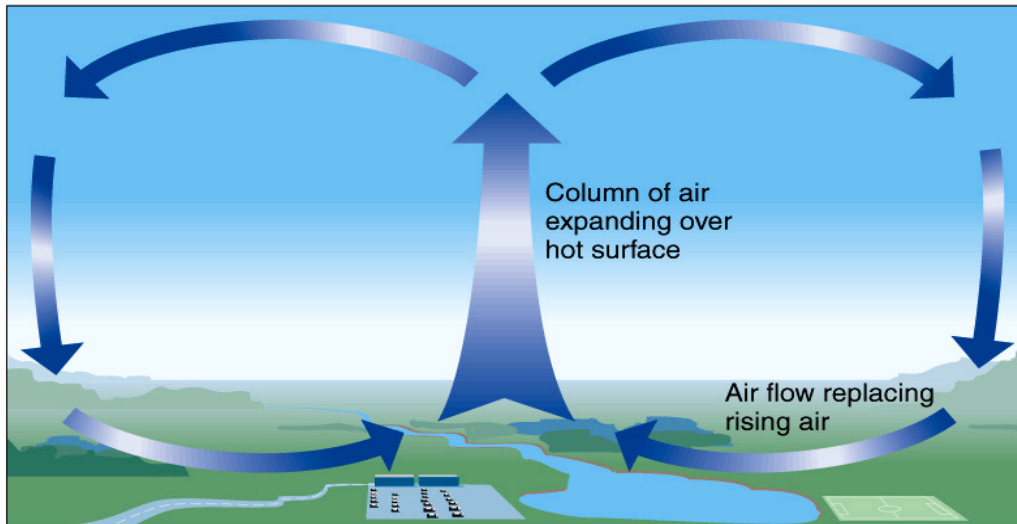
Cyclone "Winston", 02/2016

Hurricane "Kirk", 10/2024



Localized differential surface heating may lead to spatially limited **free convection**

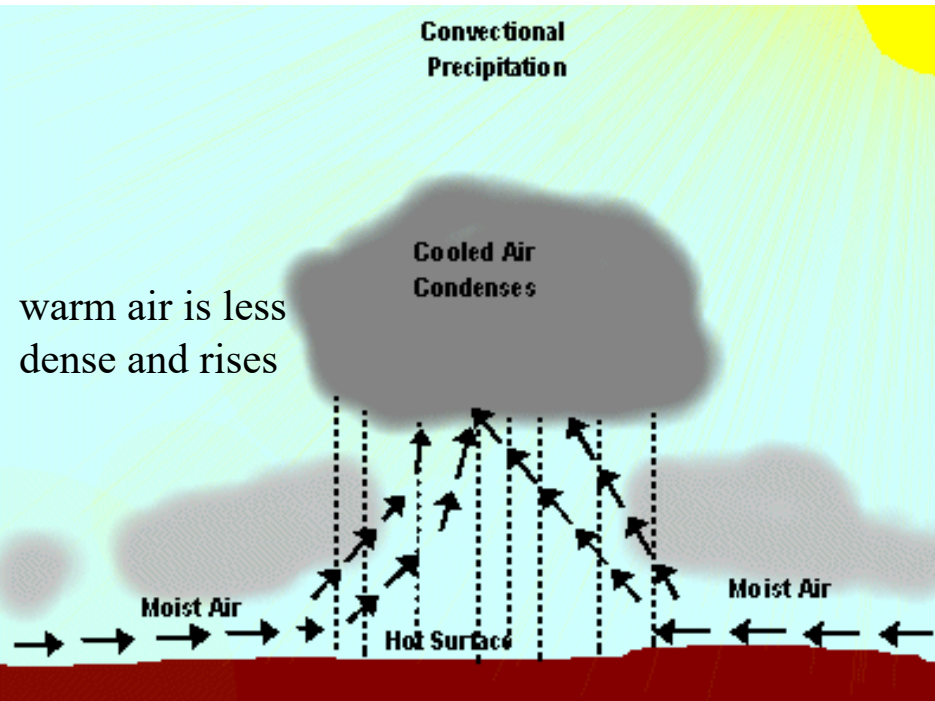
Vertical motions are stimulated from the surface upward resulting in towering clouds & possibly intense precipitation over small spatial scales



Orography, heat capacity, albedo ?



Localized convection



Lake effect snow

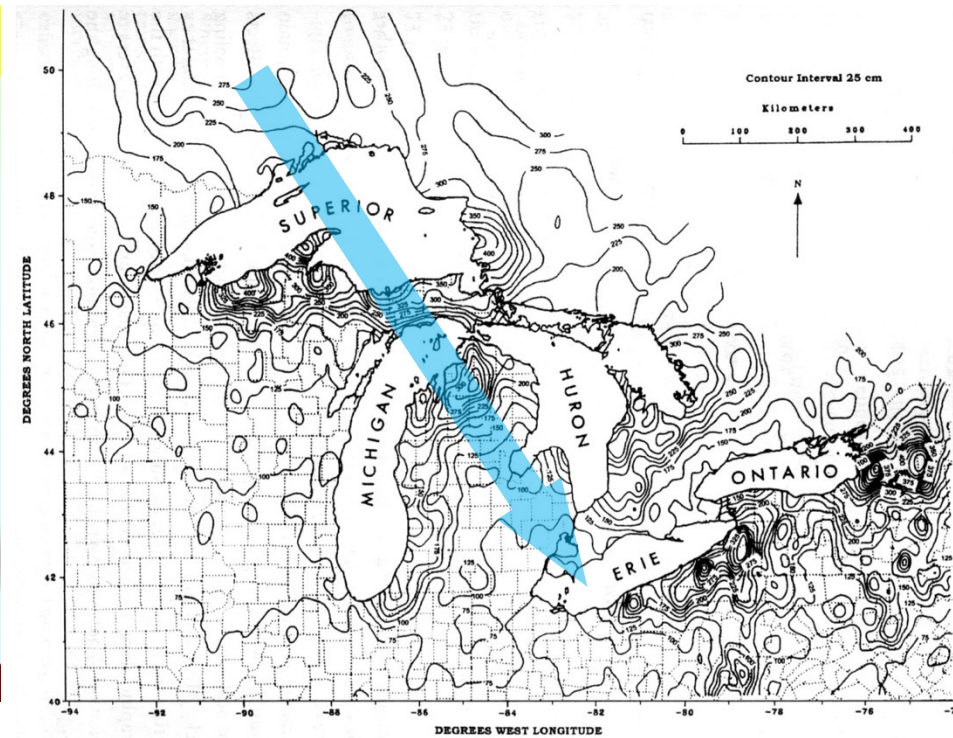
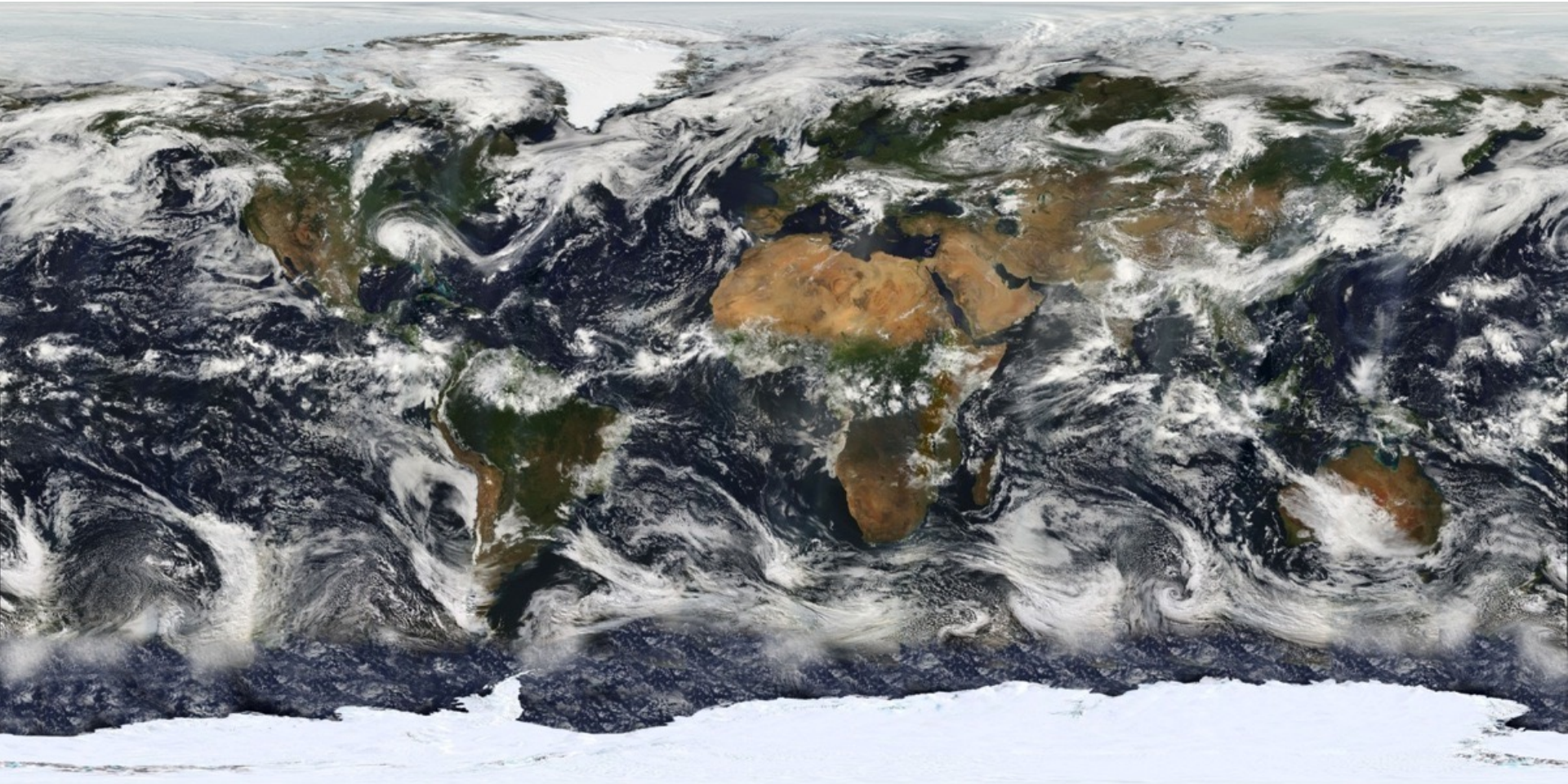
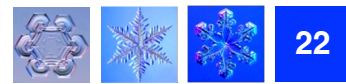


Figure 2.1. Mesoscale distribution of mean seasonal snowfall (1951–1980) in the Great Lakes region of North America, showing the influence of water bodies on snowfall over downwind uplands (after Norton, 1991).

Satellite view of the earth with characteristic cloud formations

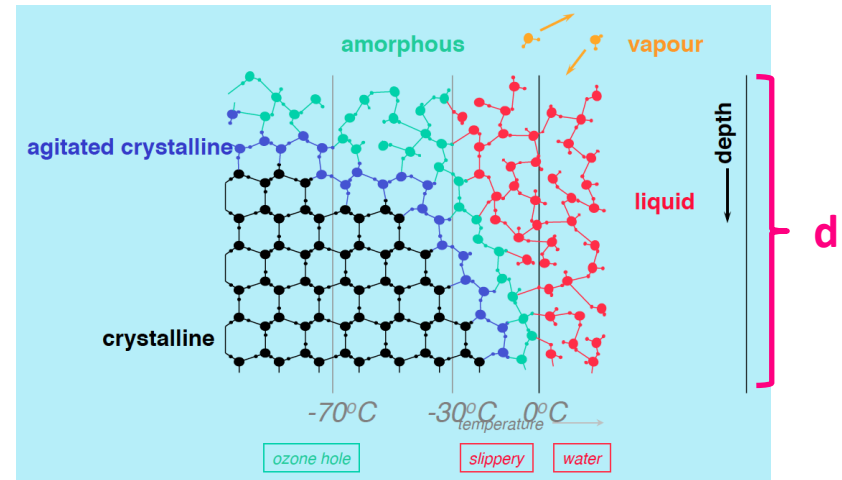
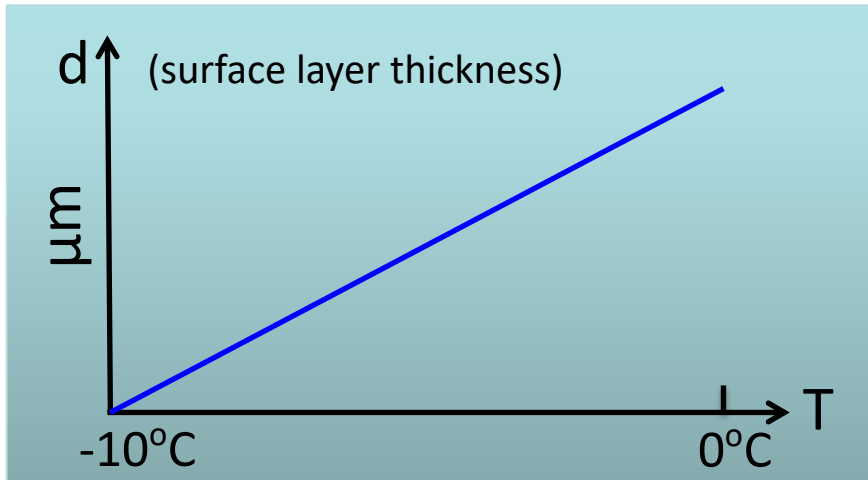


What is an ice crystal ?



in ice interior: hexagonal, regular grid/matrix of H_2O molecules with relatively strong bonds, $f(T, p) \rightarrow$ determines geometry of ice crystals

near the surface: weak bonds, high mobility of molecules \rightarrow quasi-liquid, slippery surface layer of thickness (d [micro-meters]) which is also $f(T)$:



consequence: mass transport within the surface layer film ($-10^\circ C < T < 0^\circ C$)

d is typically one to a few molecule diameters thick

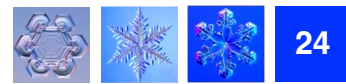
no or minimal mass transport at surface for $T < -10^\circ C$



Def. Super-cooling: lowering the temperature of a liquid or gas below its freezing point without it becoming a solid. Super-cooled water exists due to high surface tension in droplets.

Freezing of super-cooled water





In general, **condensation nuclei** (CN) are necessary to trigger droplet formation.

Typical common condensation (deposition) nuclei:

dust, soot, pollen, sea salt, combustion products, decaying organic particulates, bacteria, pre-existing ice particles

Freezing nuclei: typically, a kind of clay minerals (such as kaolinite and illite), which structurally resemble ice crystals, and which are abundant

Cooling of air may lead to

Super-cooled water droplets and

- an aggregation of water molecules
- super-cooled water droplets can exist in a liquid state between -40°C and 0°C

tiny ice crystals (embryos) in droplets

- form spontaneously in droplets
- freezing of super-cooled droplets, deposition of vapor and freezing of micro droplets on nuclei

Spontaneous freezing of water (without ICN) happens near and below -40°C

Condensation/freezing nuclei act most effectively between -25°C and -4°C

1. Homogeneous nucleation:

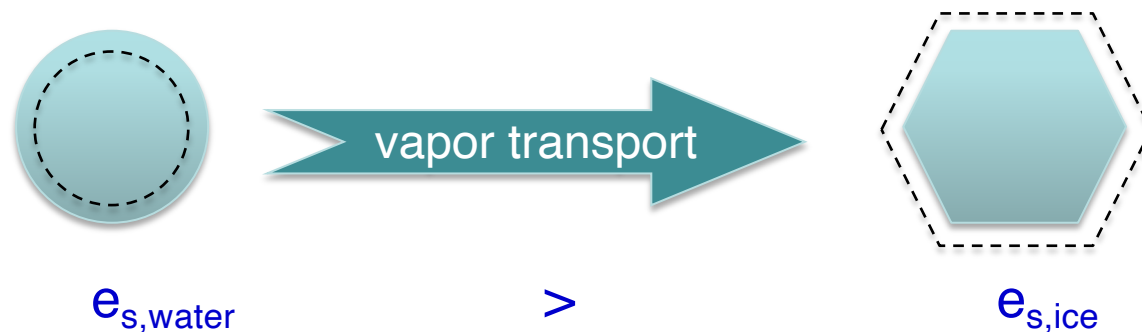
involves only water, no foreign particles

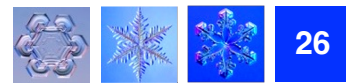
a) Spontaneous nucleation:

occurs at temperatures below -40°C

b) Ice particle (embryo) nucleation – ice nucleating particles (INPs):

- aggregation of water molecules to form spontaneously ice embryo particles
- saturation vapor pressure over water is larger than that over ice
- \rightarrow transfer of water vapor from droplets to crystals so that
- \rightarrow crystals grow and droplets shrink (Wegener-Bergeron-Findeisen process)





2. Heterogeneous nucleation:

involves water + foreign particle (cloud condensation nuclei, CCN)

a) Freezing nucleation

- condensation nuclei **within** super-cooled water droplets trigger freezing
- temperature may be $> -40^{\circ}\text{C}$ (but still cold!) ... $f(\text{droplet radius})$



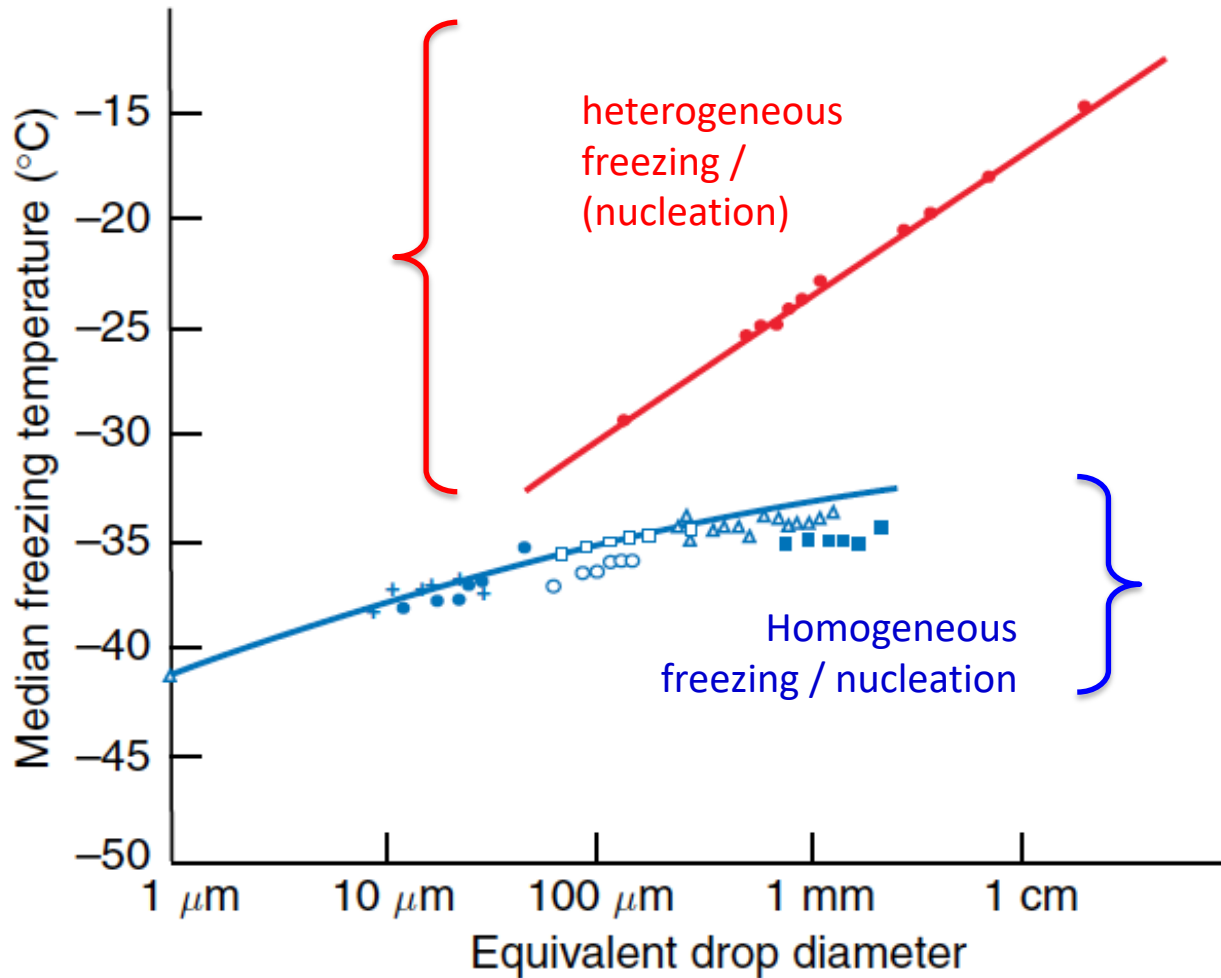
b) Contact nucleation

- super-cooled water droplets get in **contact** with CCN and freezing occurs instantly
- additionally vapor deposition occurs (Wegener-Bergeron-Findeisen process)
- (b) is more efficient than freezing nucleation (a)



Water droplets and ice crystals at same temperature may coexist in clouds.

Droplet and crystal distribution



Cloud type based on temperature

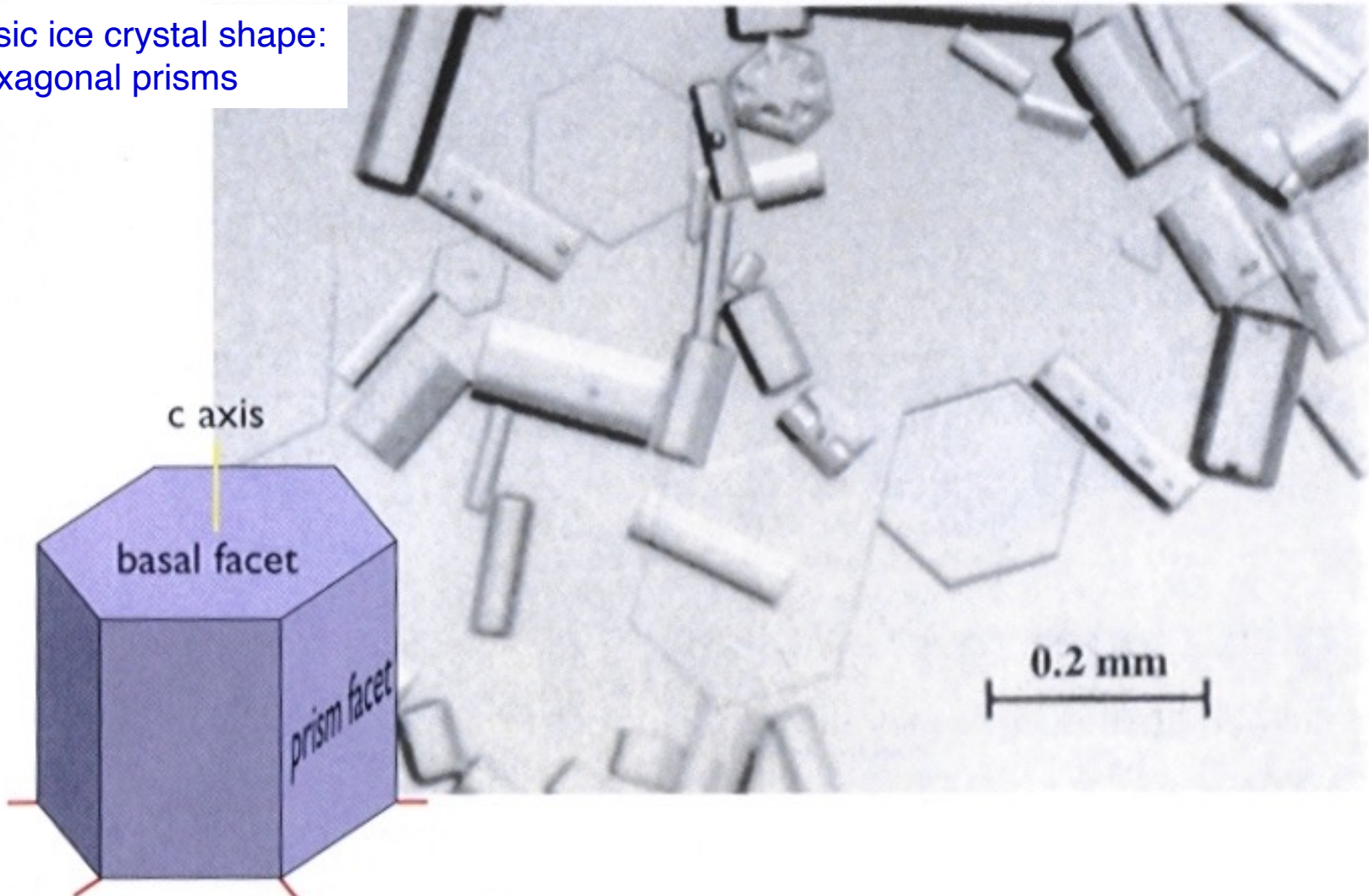
- **COLD** (glaciated) clouds contain only ice particles, e.g., Cirrus (Ci); high clouds
- **MIXED** clouds contain super-cooled water and ice (above -12°C super-cooled water dominates due to hostility of cloud environment to the freezing process), e.g., Altostratus (As)
- **WARM** clouds contain only water droplets ($T > 0^{\circ}\text{C}$), e.g., Nimbostratus (Ns)



Hexagonal ice crystals

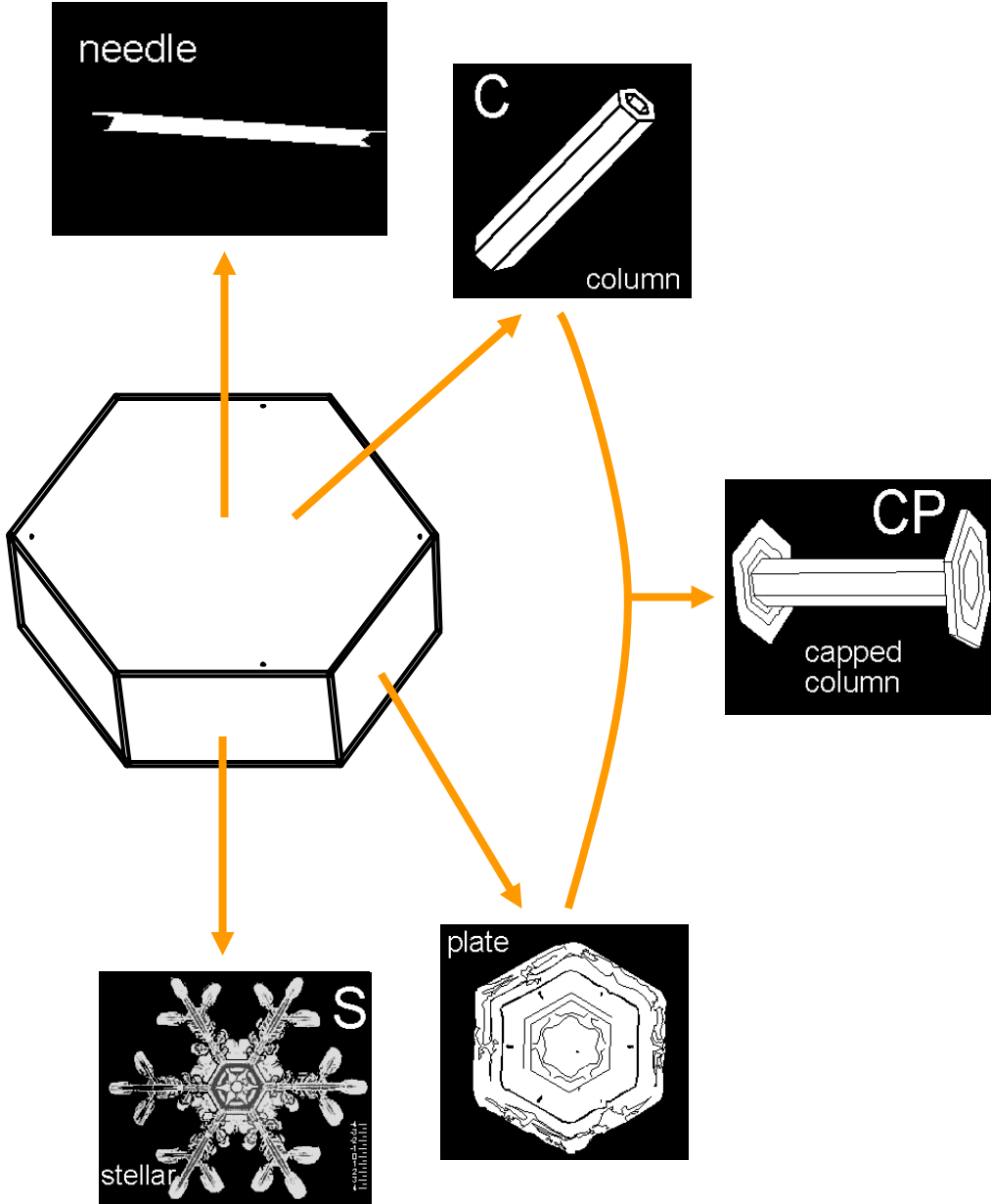


Basic ice crystal shape:
Hexagonal prisms

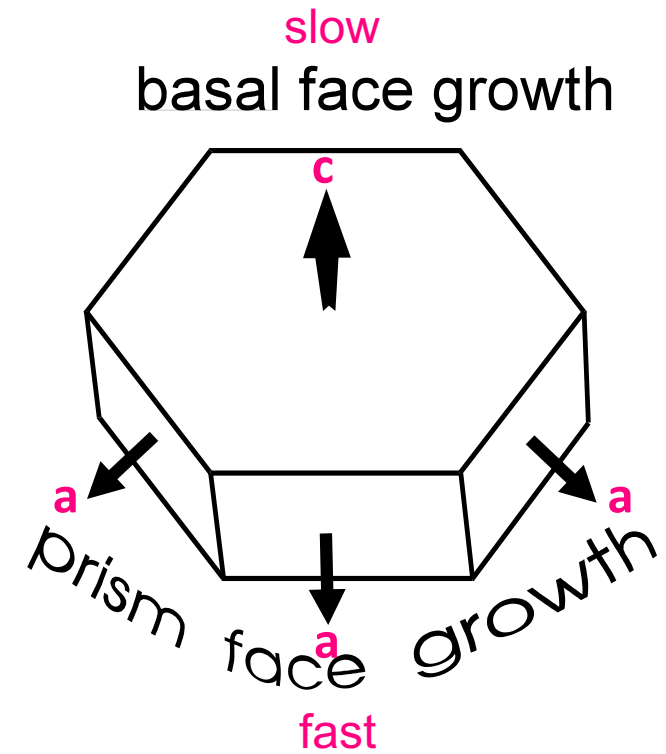


W. Tape, *Atmospheric Halos*, p. 21, © 1994 by the American Geophysical Union.

3 a axes at 120° (with respect to each other)



- 3 a-axes, 120° apart, hexagonally-symmetric
- c-axis, perpendicular to basal plane, produces columnar shape





Water Vapor + CCN or ICN + $T < 0^{\circ}\text{C}$ + Saturation

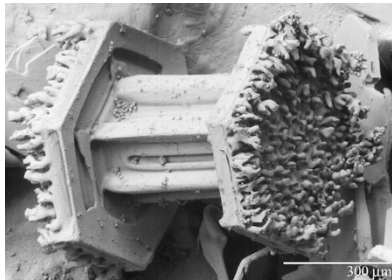
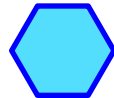
Nucleation

Ice Crystal

Snowflake

More growth: Riming, Aggregation

Ice crystal growth in the vapor phase



Air saturated w.r.t. water at a given T is **largely** super-saturated w.r.t. ice,
e.g., at -10°C by 10%, and at -20°C already by 21%

Super-saturation w.r.t. water rarely exceeds 1-2%

Super-saturation w.r.t. ice can reach values $> 40\text{-}50\%$ for very low T

→ Ice particles grow faster than droplets and even at the expense of the droplets

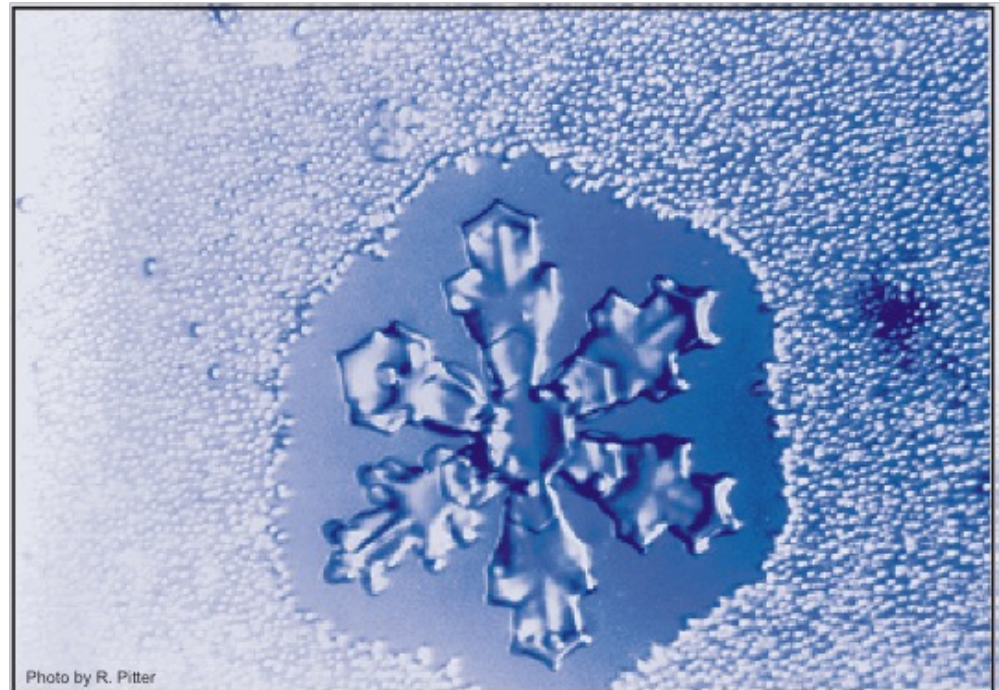
Why:

Growing ice crystal locally lowers e ,
even below saturation w.r.t. water →

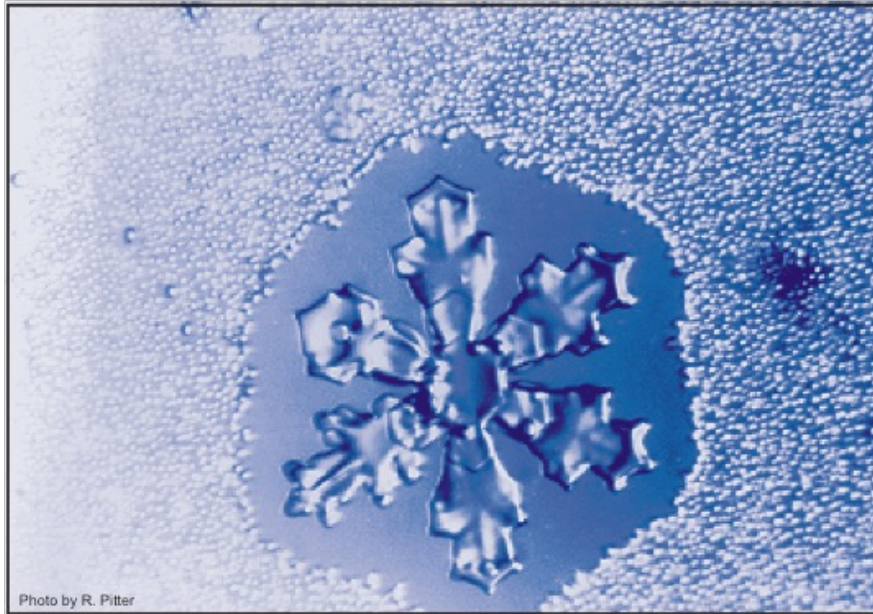
super-cooled droplets around ice
crystal evaporate (see figure
illustrating a lab-experiment)

Wegener-Bergeron-Findeisen process

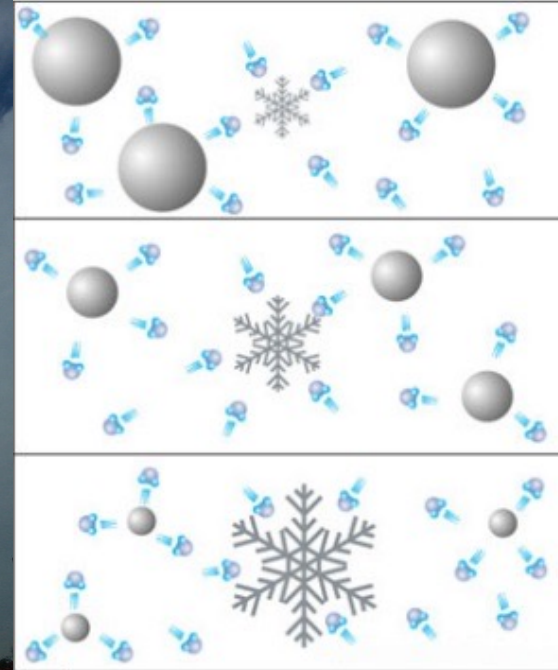
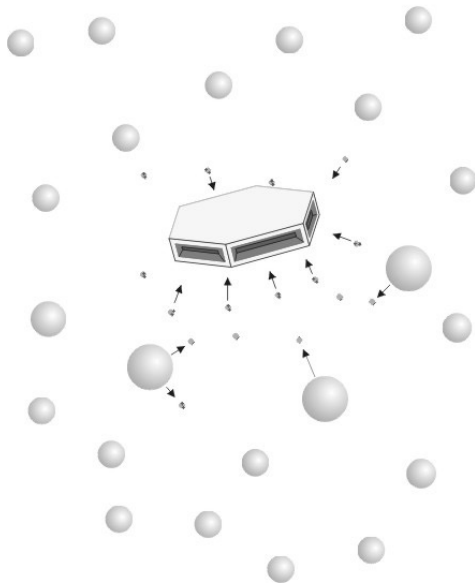
Can we observe this process
at macroscopic scale in nature?



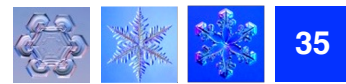
Bergeron-Findeisen process macroscopic



THE BERGERON PROCESS - Ice Growth by Vapor Deposition -



Ice crystal growth and controls



Growth processes: (a) vapor deposition, (b) riming, (c) aggregation

Growth affects/changes (1) mass, (2) volume, (3) particle diameter

Controls:

Air temperature

Degree of super-saturation

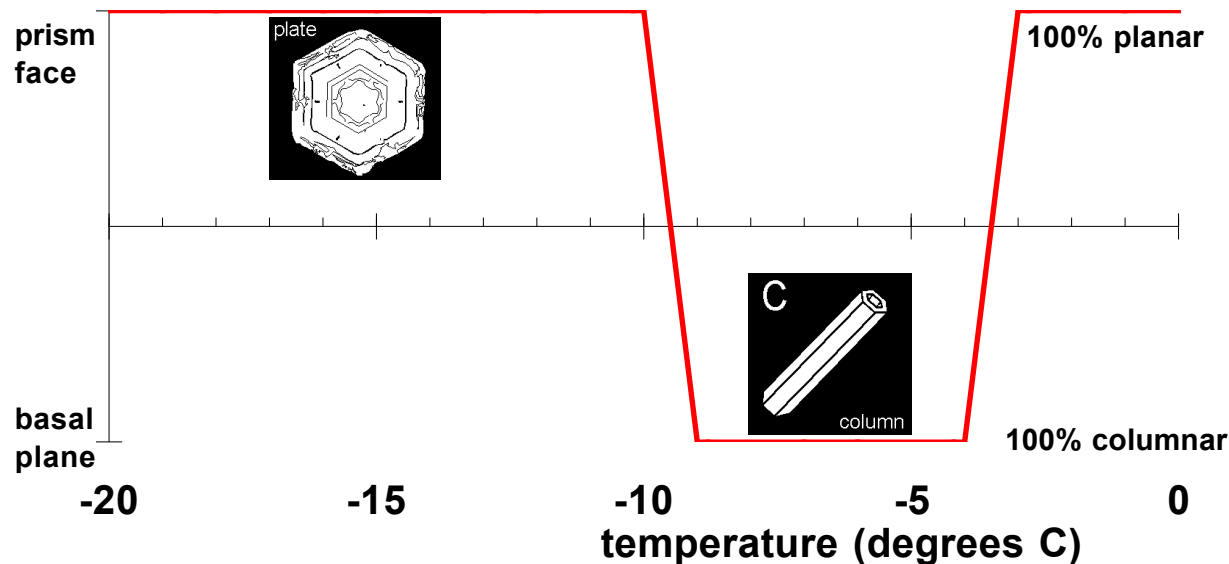
Presence of deposition nuclei

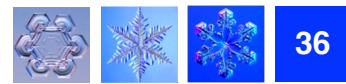
Efficiency of the ice nuclei

Cloud type

Particle size (distribution)

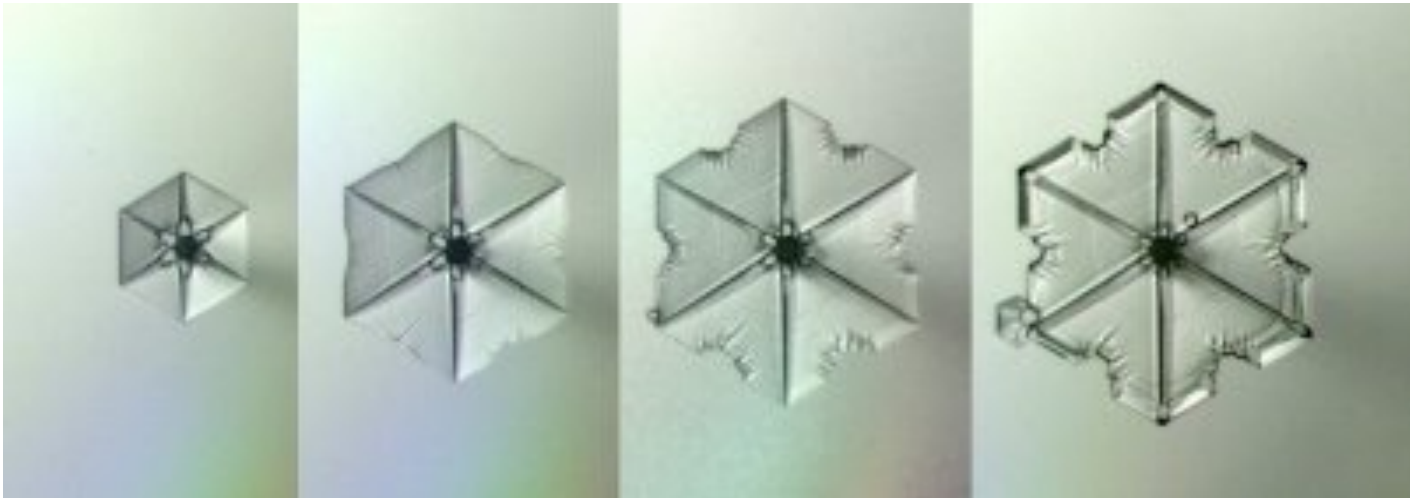
- Atmospheric history after initial deposition (evolution / mixture)



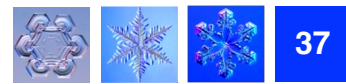


Diffusion controlled growth of ice crystals (in mixed phase clouds)

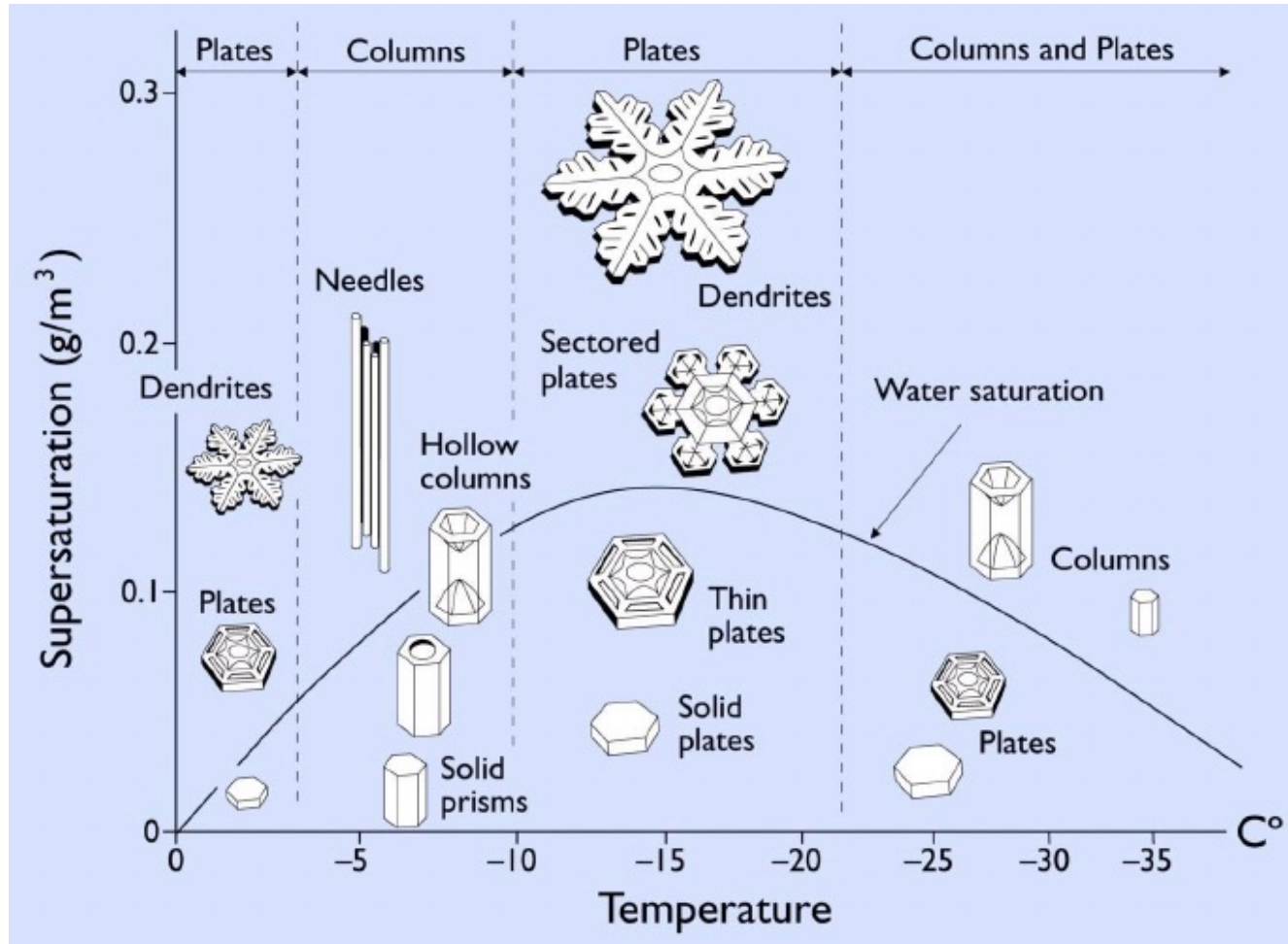
- occurs because vapor pressure over ice is smaller than over water
→ droplets evaporate and vapor deposits onto ice particle surfaces
→ ice particles grow faster than droplets; → $N(\text{ice}) \gg N(\text{water})$
- max growth rate of ice crystals occurs between -15°C and -12°C
- timing: rapid growth for first 1/2 hour then process slows down
- cannot produce large crystals or snowflakes



Types of snow / ice crystals



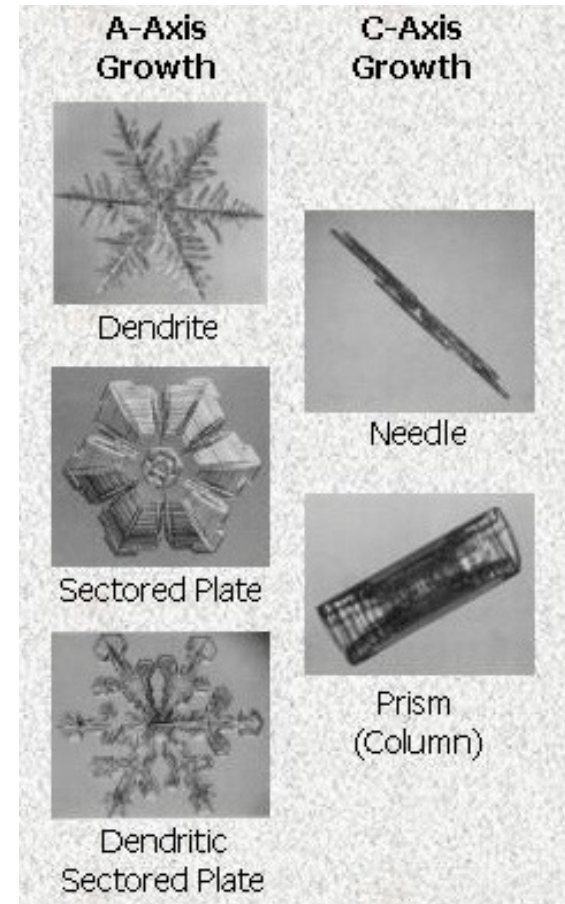
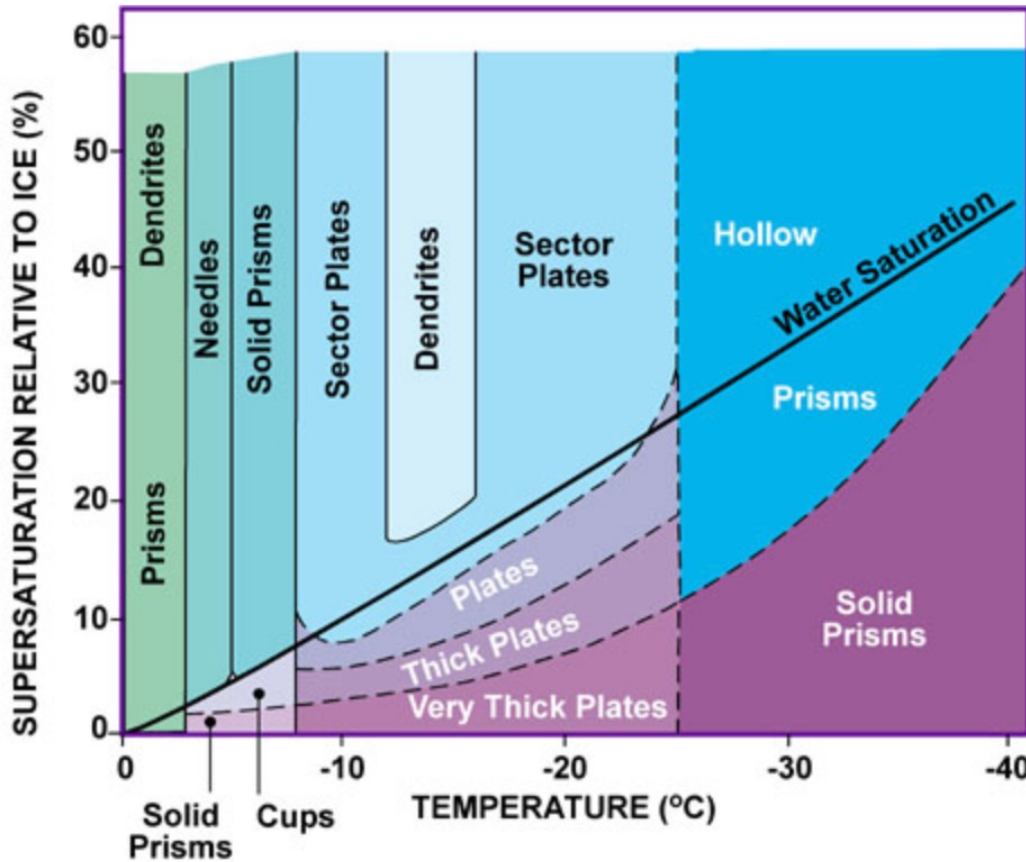
Type of crystal f (T, super-saturation):
High super-saturation produces complicated (stellar) crystals
Low super-saturation produces hexagonal plates



The Nakaya snow crystal morphology diagram, showing different types of snow crystals that grow in air at atmospheric pressure, as a function of temperature and water vapour supersaturation relative to ice. The water saturation line gives the supersaturation of supercooled water, as might be found within a dense cloud. Note that the morphology switches from plates ($T \approx -2\text{C}$) to columns ($T \approx -5\text{C}$) to plates ($T \approx -15\text{C}$) to predominantly columns ($T < -30\text{C}$) as temperature is decreased. Temperature mainly determines whether snow crystals will grow into plates or columns, while higher supersaturations generally produce more complex structures.

After K. Libbrecht

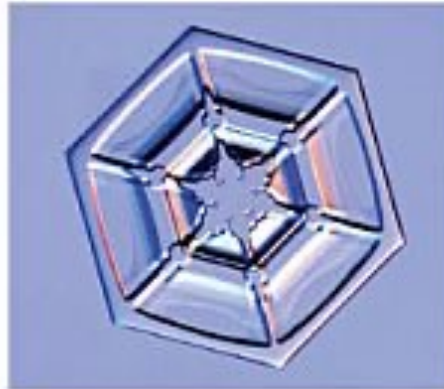
Super-saturation & crystal shapes



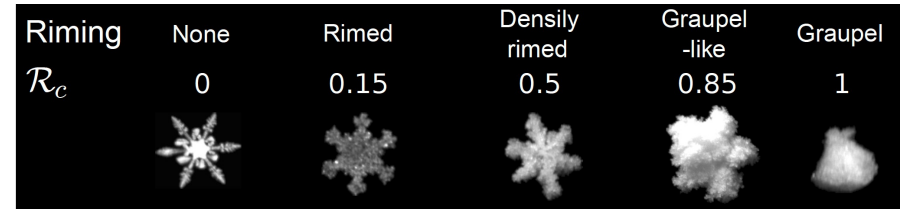
High super-saturation:

- growth occurs where vapor density is highest (high radius of curvature)
- growth occurs at edges & corners, where electrical charges not balanced

Atmos. ice crystals (examples)



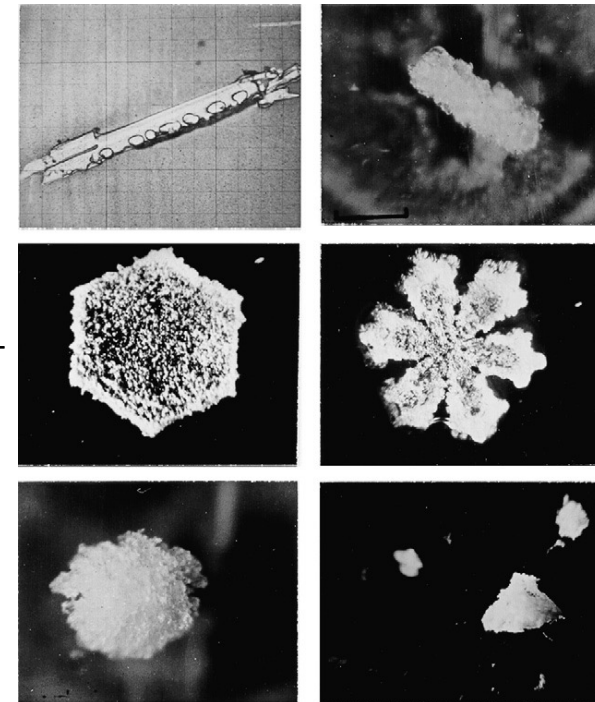
- **adhesion / accretion** of super-cooled water droplets to an ice particle or snow crystal (equivalent to collision – **coalescence** growth in liquid droplets)
- very efficient and fast process
- range of rime types:
 - rimed crystal (ice crystal w/droplets)
 - graupel (aggregates of frozen droplets)
 - hail (round pellets)
 - sleet (partially melted and refrozen)



Praz et al. 2017



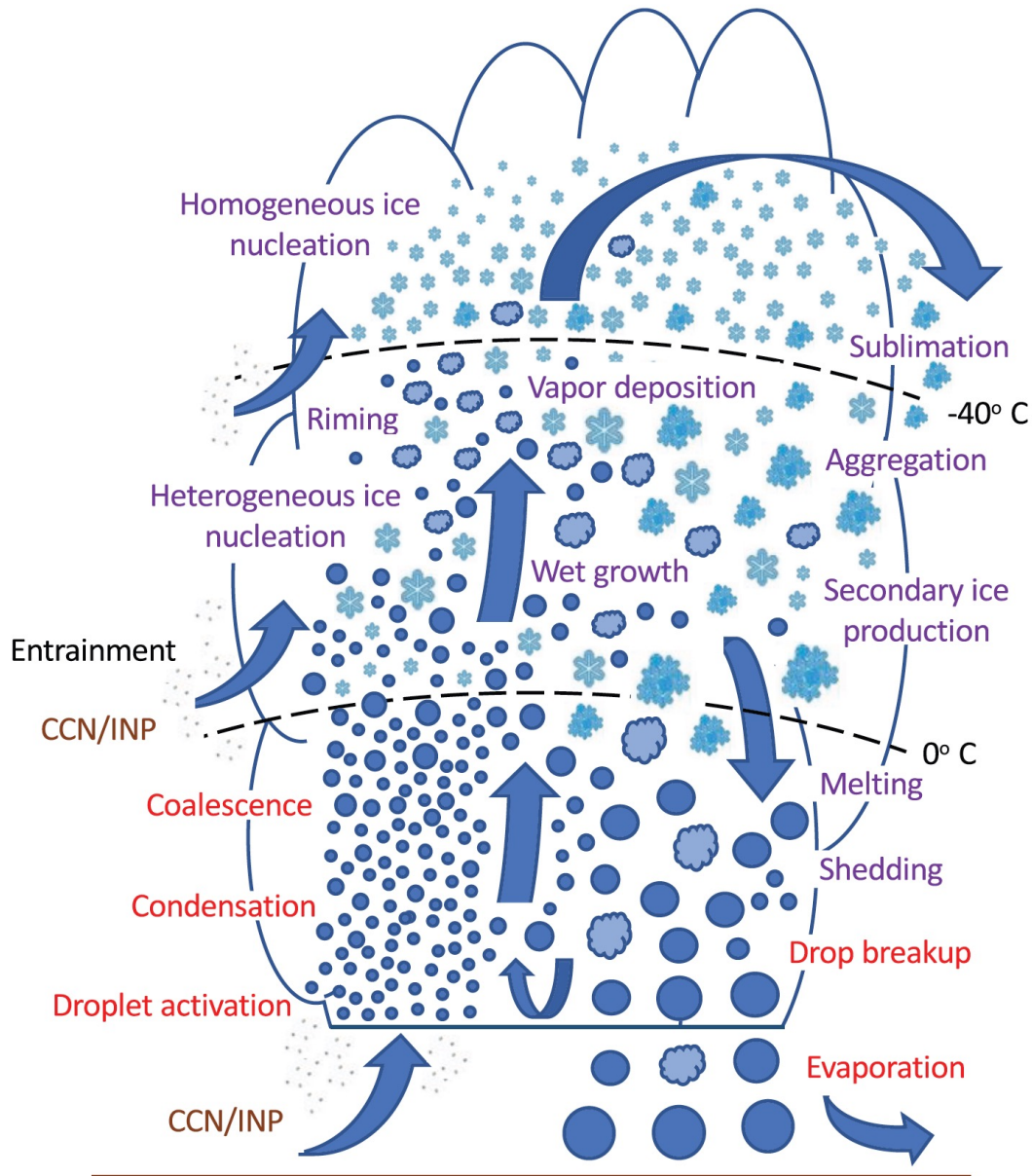
Wallace and Hobbs: Atmospheric Sciences



Growth by **aggregation**:

- Shapes are formed by collision and adhesion (collection) of ice crystals
- Fast growth rate: from 1 to 10 mm in 20 min
- Can produce large snowflakes (up to a few cm)
- Mass is sufficient that they fall to the ground
- Interaction of crystals and contact with super-cooled droplets leads to formation of snowflakes or rounded shapes.
- Riming ... Graupel -> Hailstones





Schematic overview of processes contributing to the formation of solid precipitation formation

Controlling variables:

- Air temperature
- Pressure
- Level of saturation
- Availability of
 - Liquid water
 - Condensation nuclei

upward looking radar:

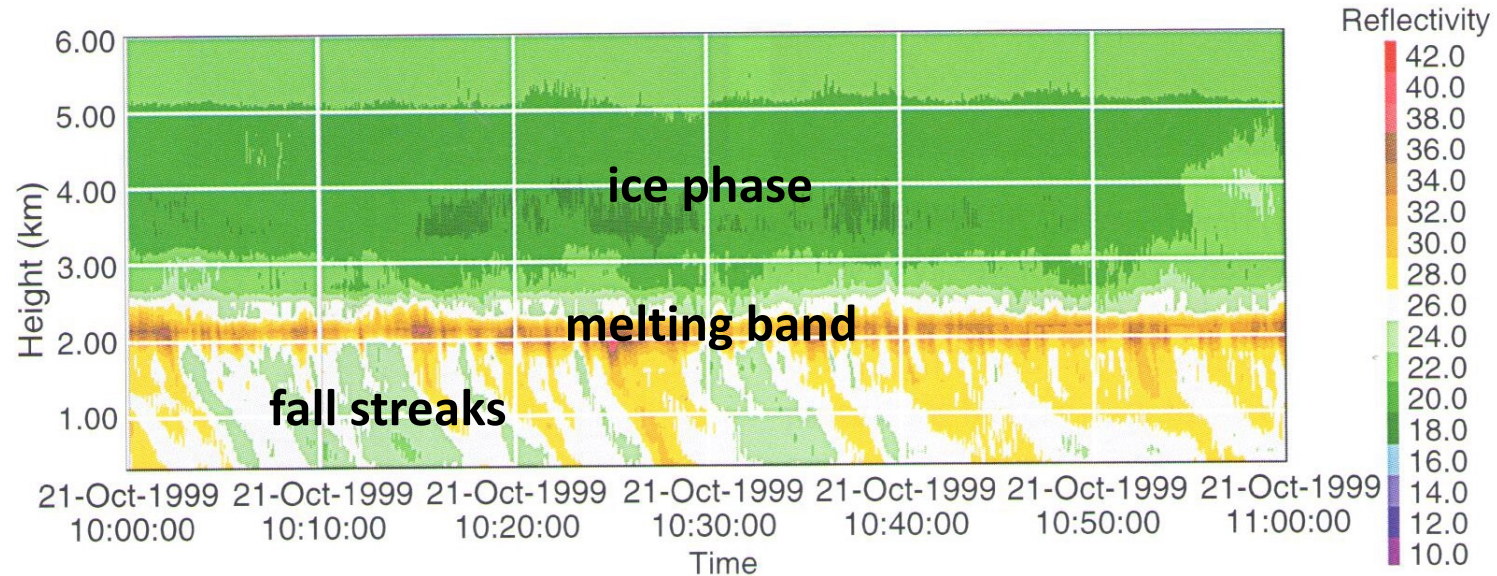


Fig. 6.45 Reflectivity (or “echo”) from a vertically pointing radar. The horizontal band of high reflectivity values (in brown), located just above a height of 2 km, is the melting band. The curved trails of relatively high reflectivity (in yellow) emanating from the bright band are *fallstreaks* of precipitation, some of which reach the ground. [Courtesy of Sandra E. Yuter.]

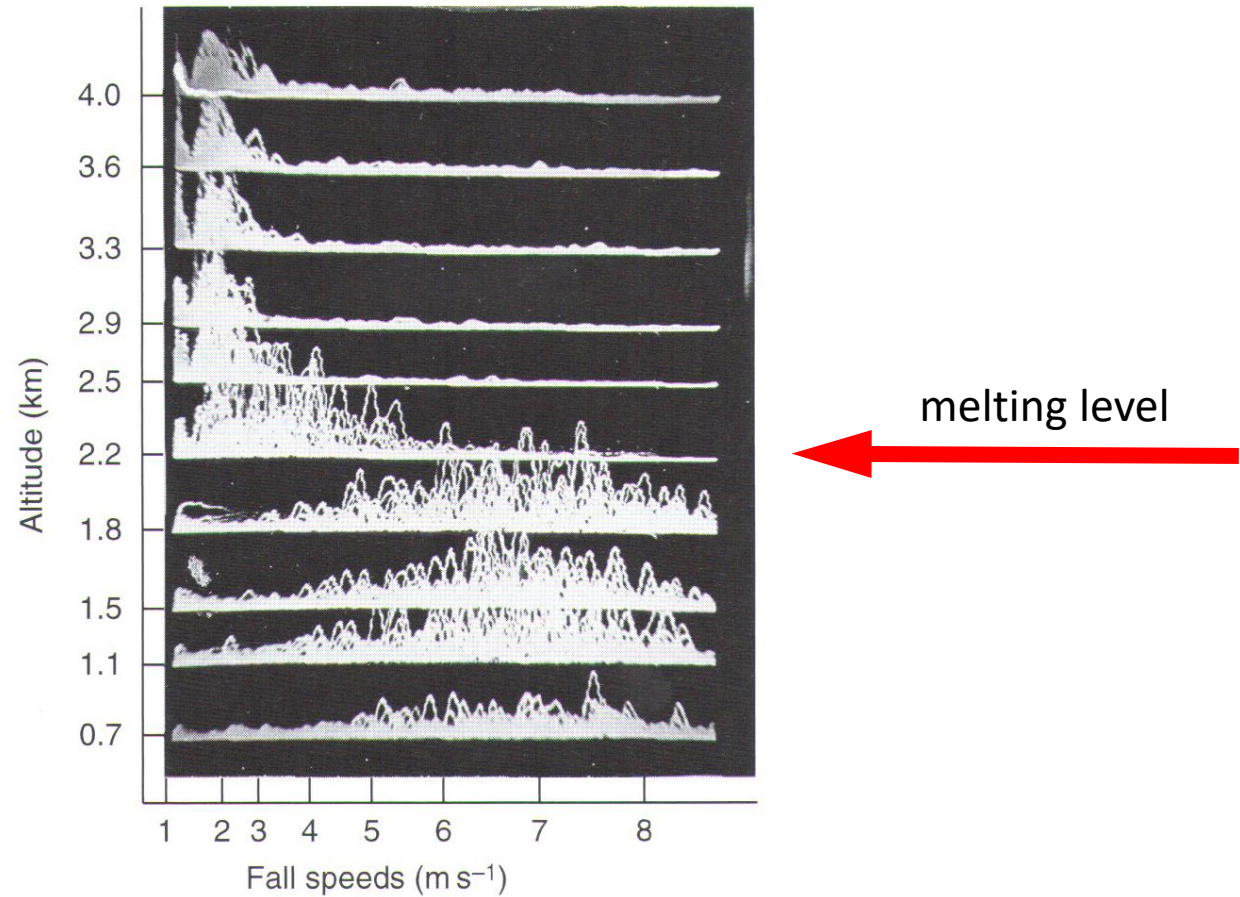
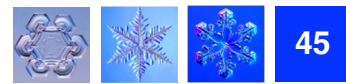


Fig. 6.46 Spectra of Doppler fall speeds for precipitation particles at ten heights in the atmosphere. The melting level is at about 2.2 km. [Courtesy of Cloud and Aerosol Research Group, University of Washington.]



Snowflakes can pass through different temperature and water vapor regimes as they fall through the atmosphere.














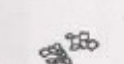






Example: capped columns start as columns (in cold, dry air) and caps grow as crystals pass through warmer air

Collision/adhesion increases crystal complexity

Riming modifies crystal shape (rimed crystal, hail, sleet)

When mass and size pass critical threshold, gravitational settling starts and crystals / snowflakes / grains fall from cloud to ground.



Code	Graphic Symbol	Typical Forms	Terms
1			Plates
2			Stellar crystals
3			Columns
4			Needles
5			Spatula dendrites
6			Capped columns
7			Irregular particles
8			Graupel (soft hail)
9			Ice pellets (Am. sleet)
0			Hail

Type of particle (F)

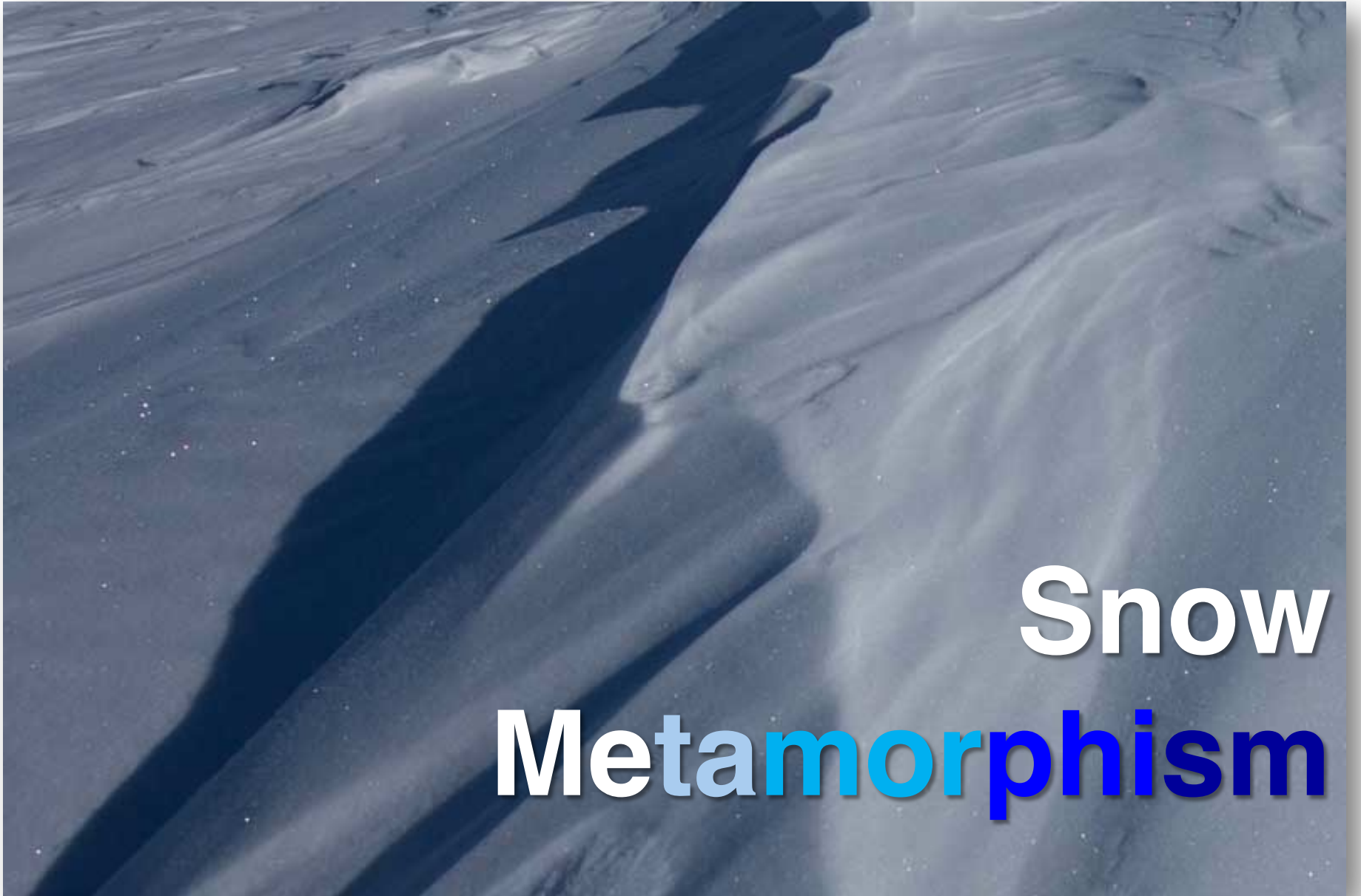
Figure 2.4 Snow crystal forms from the international classification system for solid precipitation (adapted from Mason, 1971).

National Research Council, 1954. *The International Classification of Solid Precipitation*. IASH, Techn. Memo 31, NRC, Ottawa, Canada.

Others include:

Nakaya, U., 1954. *Snow Crystals: Natural and Artificial*. Harvard University Press, 510pp.

Magono, C., and C. Lee, 1966. Meteorological classification of natural snow crystals. *J. Fac. of Science, Hokkaido University, Series VII(2)*: 321-335.



Snow Metamorphism